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ELECTRICAL ENGINEERING

FOR ELECTRIC LIGHT ARTISANS AND STUDENTS

(EMBRACING THOSE BRANCHES PRESCRIBED IN THE SYLLABUS ISSUED BY THE CITY AND GUILDS TECHNICAL INSTITUTE)

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WITH 346 ILLUSTRATIONS

NEW AND REVISED EDITION

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PREFACE

TO

THE FIRST EDITION

WE have frequently been asked by artisans and students to recommend a single work covering the whole field of Electric Lighting. Our inability to comply with this request has prompted us to endeavour to fill such a palpable gap in the literature of technical science. We have designed this book to cover the extensive syllabus of the City and Guilds of London Institute, and have so enlarged its scope as to make it embrace the requirements, not only of those actually employed in the electric lighting industry, but also of those who, while having little or no electrical knowledge, have under their supervision various kinds of electrical machinery. The work should therefore prove of service to such men as marine, railway, and tramway engineers, naval officers, municipal officials, and managers of mines and factories.

We recognise to the full the fact that, as a rule, the most successful electrical engineers are evolved from good mechanical engineers, and have striven to give our readers, even though they may possess no previous electrical knowledge, a clear insight into the purely scientific as well as the practical part of the subject. Every effort has, however, been made to embrace only the essen-

tial branches of the pure science, omitting those which, while interesting and serviceable in other fields, are not required in electric lighting or the electrical transmission of power. It is hoped also that we have succeeded in the difficult task of explaining the subject clearly and in simple language. The close connection between the three kinds of electrical phenomena, static or frictional, dynamic or current, and magnetic, has been carefully explained and made to follow naturally. It is believed that the fact that magnetism is primarily but a consequence of dynamic electricity, or the more or less permanent effect on certain substances of an electrical disturbance, instead of being a separate and distinct series of phenomena, has not hitherto been so plainly and unhesitatingly expressed. It is our firm conviction that, in the near future, this view of the question is the one which will be universally adopted. The conception of 'lines of force' is one of great value to the student, and he will find them here reasoned about as having a tangible existence. It would be impossible to describe every piece of apparatus or machinery in actual use, and we have selected those which, while having proved in practice to be among the best in their respective classes, also serve to illustrate in the clearest manner the laws and principles involved. In a few cases, however, the apparatus can scarcely be said to have been successfully applied, but they have been introduced as indicating the highest present developments in directions in which success will probably be attained.

Although primary batteries are not used to any great extent in electric lighting, except for testing and other similar operations, yet a considerable amount of space has been devoted to them, and to the experiments which can readily be performed by their aid, because long experience has taught us that they afford in the readiest way a clear insight into the fundamental principles of the science and the various laws so far discovered.

An unusually large number of the explanations have been

based upon Ohm's law and its consequences. Mathematical formulæ and explanations have, where possible, been avoided; where they do occur they are invariably simple, and are generally accompanied by arithmetical examples. As they merely supplement the ordinary explanations, they can usually be ignored without the meaning being missed; but those able to solve a simple equation will find very little indeed which cannot easily be followed.

NOTE TO THE REVISED EDITION

Since the first edition of this book was published, less than five years ago, considerable strides have been made in the development of the science and practice of Electrical Engineering. We have therefore considered it desirable to thoroughly revise the work, and it is hoped that, in its new form, it will prove as acceptable as the many editions which have been called for have shown it to have been in the past.

W. S.
A. B.

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ELECTRICAL ENGINEERING

CHAPTER I.

CURRENT—POTENTIAL—CONDUCTORS—INSULATORS

WHEN a stick of sealing-wax is rubbed with a piece of dry fur or flannel, the wax acquires the power of attracting to itself any light substances that may be in its vicinity. By taking suitable precautions a like power can be detected in the fur or flannel. Similar phenomena can also be produced by the rubbing together of other substances, such as glass and silk, india-rubber and silk, brown paper and a bristle clothes-brush. A body which exhibits this power of attraction is said to be endowed or charged with electricity, or to be electrified.

But there are two electrical states, and this can be easily proved; for if by means of a foot or so of silk ribbon we suspend the electrified sealing-wax and bring near it another electrified stick of sealing-wax, repulsion ensues—that is to say, the suspended rod recedes from the approaching one. On the other hand, if certain necessary precautions have been taken to prevent the neutralisation or escape of the electricity that was generated on the fur or flannel rubber, it will be seen that, on bringing it near the suspended sealing-wax, attraction takes place. A similar result would follow if a warm glass rod were rubbed with a piece of dry silk and then brought near the sealing-wax. On suspending, however, the electrified glass and bringing the electrified fur near it, repulsion would take place. It is manifest, then, that as electrified glass attracts electrified sealing-wax, but is repelled by

or repels electrified fur, there are two electrical states, one on the sealing-wax, which is called negative, and the other on the fur, which is called positive. It is also clear that bodies similarly electrified are mutually repellent, while bodies dissimilarly electrified are mutually attractive. This matter will again be referred to, but the points to which especial attention is now directed are, first, that the amount of positive electricity on the one body is always equal to the negative on the other; and, secondly, that the amount of electricity developed by rubbing the two bodies—say the sealing-wax and the fur—together, bears no direct relation to the amount of actual friction to which the bodies are subjected, for what is really essential in order to obtain the highest possible degree of electrification is to bring every portion of the one surface into intimate contact with every superficial particle of the other, and when that is done, no extra amount of rubbing can develop any further degree of electrification.

Speaking generally, then, it may be said that when any two bodies are rubbed together electricity is produced, although it frequently happens that the amount is so small as to render its detection very difficult. If, however, delicate apparatus, which we will not pause here to describe, is employed, very feeble charges can be indicated. In fact, if a piece of zinc and a piece of copper are simply placed in contact the feeble charge of electricity then developed can easily be rendered evident. If the same pieces of metal are dipped in saline or acidulated water, a similar result follows, although in this case the water itself becomes an important factor in determining the resultant electrification. The end of the zinc outside the liquid will be found to possess properties similar to those of the sealing-wax after it has been rubbed with fur. It is, therefore, said to be negatively electrified. The copper, on the other hand, will have an electrical state similar to that of the fur itself, or of the glass which has been rubbed with silk, and it is therefore said to be positively electrified.

It follows that whether the electricity is the result of so-called friction or whether it is a consequence of the simple contact of two dissimilar bodies, it is with precisely the same *kind* of force that we have to deal, and the old distinction between 'frictional' and 'galvanic' electricity, which used to be urged with consider-

able persistence, is virtually a myth. The quantity of electricity may vary, and we may view it in its two phases, positive and negative, but neither of these considerations can affect the character of the force.

It may be accepted as a general fact that when the same kind of force is bestowed upon two points or bodies, but to a different extent in the one case as compared with the other, there is a universal tendency to equalise the distribution of the force—that is to say, to produce equilibrium, and this equilibrium will be established when the conditions become such as to render it possible. Reverting again to the zinc and copper plates partly immersed in water, the exposed ends will be electrified to different degrees. There will be a tendency to produce equilibrium, or, as it is more generally called, neutralisation. This will be accomplished if the necessary facilities are afforded, and until this is done the intervening space will be subjected to what may be called an electrical stress. It is found by experiment that a piece of metal affords the readiest means of relieving the strain due to this stress, thus facilitating neutralisation, for on joining the two plates together, say by a piece of copper wire, a momentary rush of electricity from the one to the other will take place. This phenomenon is that which is generally known as discharge, and it affects the whole combination, including the liquid and the metal surfaces in contact with it.

This brief spasmodic flow or rush of electricity, whose function it is to restore the electrical equilibrium, causes, however, a series of chemical changes to take place in the liquid itself, among other things a portion of the zinc being dissolved and converted into what is called a salt of that metal. These chemical reactions cause in their turn a fresh electrical difference between the plates, which is followed immediately by another equilibrating flow, and that by a further difference, and so on. These changes follow one another in exceedingly rapid succession, so rapid, in fact, that it is a matter of absolute impossibility to distinguish them separately, and we have consequently what appears to us as, and what is known as, a continuous 'current' of electricity.

A little reflection will make it evident that by following out the line of experiment and deductions here indicated, the so-

called single and double fluid theories of electricity are both disregarded, not simply for the sake of disregarding them, but because they are unnecessary and involve considerations and concessions which are not warranted by the circumstances. In point of fact, electricity is not a fluid at all, and only in a few of its attributes is it at all comparable to a fluid.

Let us rather consider electricity to be simply a form of energy which imparts to material substances a peculiar state or condition, and that *all* such substances partake more or less of this condition, just as we say that all bodies are heated, although to varying degrees, and that in virtue of this heat their particles are set into more or less rapid vibration.

Moreover, as in the case of a heated body, there is a region surrounding an electrified body in which the force due to the tendency to produce electrical equilibrium can be made evident. This is shown by the fact already referred to that two bodies in a similar electrical state repel one another, while others in different electrical states attract. It is inconceivable that such an effect as the imparting of motion to a mass of matter can be produced without the aid of some medium capable of transmitting the force. What this medium actually is is a matter of doubt, and we cannot experimentally determine the question. So also is the mode or method of transmission. Under such circumstances it becomes convenient to picture to ourselves the propagation by means of *lines of force*, travelling through an infinitely elastic, imponderable medium, or substance, as it is sometimes called, which is assumed to pervade all matter and all space, and which is known as 'ether.' Granted that these lines of force may have no actual existence, the conception is, nevertheless, exceedingly useful, and facilitates an accurate estimation of the way in which electrical phenomena are set up, so much so, that the idea imperceptibly grows upon the student, and to him the lines of force become endowed with a definite meaning.

There are three features about these lines of force to which we may draw attention. In the first place, their assumed position indicates the path along which the action takes place; secondly, their direction in this path indicates the direction in which the force is transmitted; and, thirdly, their density, or the number

occupying a given space, measures the strength or magnitude of the force. Having given to these lines of force position, direction, and density, we can predict the result which should follow in any given electrical field. For the action is always as if the lines of force endeavour to coincide in direction, and then to shorten themselves, the magnitude of the action being simply dependent upon the density of the lines.

In the case of an electrified sphere suspended somewhere in space and remote from every disturbing element, the lines of force would be radial and equidistant in position, their density would depend upon the degree of the electrification or the quantity

FIG. 1.

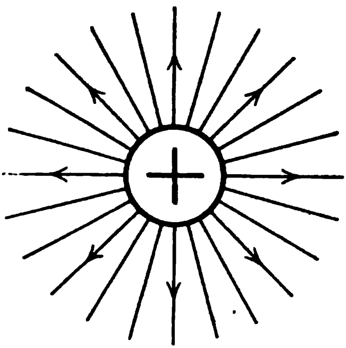
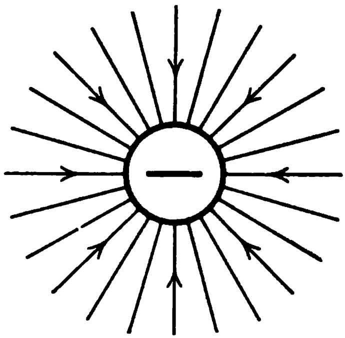


FIG. 2.



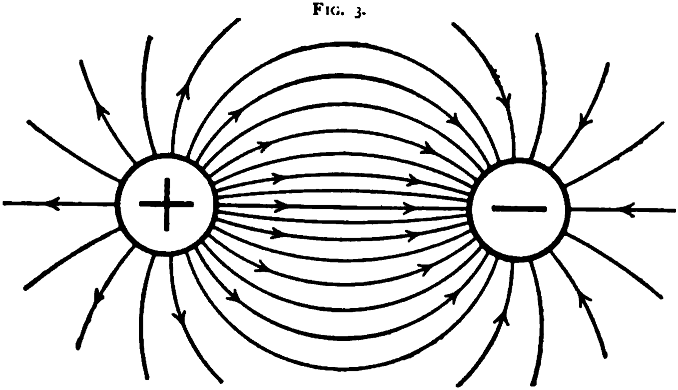
of the charge, while their direction—that is, radially inwards or radially outwards—would depend upon whether the charge were negative or positive.

Let us assume a positively charged sphere (fig. 1) to be suspended, with its lines of force directed outwards, and a second sphere, negatively charged (fig. 2), with its inwardly directed lines of force, to be brought into the vicinity of the first sphere ; it will be evident that many of the lines of force of the two spheres will bend or turn round and concentrate themselves within the space intervening between the spheres in the manner shown in fig. 3. The lines of force will now be similar in direction, and, owing to the shortening tendency above referred to, attraction results.

The attraction, presuming it to be sufficiently strong, will

impart motion to one or both of the spheres, or, in other words, work will be performed. Now this capacity for doing work arises solely from the electrification, and the quantity of work performed is proportional to the degree of electrification. But 'capacity for doing work' and 'potential' are convertible terms—that is to say, anything which possesses the capacity for doing work may be said to have a certain potential, consequently the degree of electrification of any body is known as its potential. We have previously said that the tendency to produce, between two electrified points or bodies, a state of electrical equilibrium, is proportional to the difference of their degrees of electrification. In technical language

FIG. 3.



this means proportional to their difference of electrical potentials. Therefore, in the case of the zinc and copper plates immersed in acidulated water, the flow of electricity from the exposed end of the copper to the exposed end of the zinc is correctly described as being due to a difference of potential between those ends.

If the student has grasped what has already been said, he will be able to readily apply the doctrine of potential to special cases; for example, it will be evident that no two parts of the same body (providing it is one that can transmit or propagate the flow of electricity) can remain for any length of time at different potentials; for the moment a difference of potential is established an electrical stress is set up, and the flow of electricity follows as a necessary or natural consequence. On the other hand, where

there is no difference of potential there can be no flow of electricity. So that we come to these conclusions—viz. that electricity always flows between two bodies which are at different potentials ; that it flows from the body possessing the higher to that possessing the lower potential ; that in the case of the 'current' maintained by the 'simple cell,' composed of zinc and copper plates dipping into acidulated water and referred to in a previous page, we had a difference of potential established on the zinc and copper extremities ; that on joining these extremities together there was a flow of electricity to produce equilibrium ; that this, by means of the chemical changes, re-established a potential difference ; and that these actions and reactions, being alternated with almost infinite rapidity, appear to us as a continuous current.

We may, therefore, define a 'current' as the expression of an effort ever being made to establish electrical equilibrium between two points which are ever being electrified to different potentials. Neither of these objects is attained - that is to say, a difference of potential is never permanently established on the one hand, and, on the other, equilibrium it is impossible to maintain.

Let us further consider the case of the simple cell, the zinc and copper of which, however, instead of being joined together, are each connected to long pieces of wire, whose other or free extremities are inserted in the earth at different places. It used to be the general assumption that in this case the current would flow from the copper plate to the earth, and through the earth to the other wire, up which it would pass and so return by the zinc to the battery. But anything more unreasonable than such an hypothesis it is really impossible to conceive, more particularly when the distance between the two earth connections is considerable. To demonstrate this we need only take into consideration the state of affairs at the Central Telegraph Office in London, where there are upwards of, 1,000 different circuits or lines, one end of each battery being joined to the same earth plate under the building, the other ends being joined to the respective lines, which in their turn are joined to earth plates at the distant ends. Viewed in its real aspect, this 'earth-return' theory compels the assumption that the 1,000 currents which go to earth at as many

different places—some at Newcastle, some at Liverpool, others at Cardiff, Yarmouth, &c., others, again, only a few hundred yards away in several of the City thoroughfares—all return through the earth to the earth plate or connection under the Central Office, where each individual current has to pass the other 999 currents travelling through the plate, and single out the particular wire joined to the particular battery from the other end of which it emanated, and is not satisfied or has not completed its work until it thus gets safely home again. Moreover, these currents do not all travel in the same direction either to or from London, so that, were they really to complete their path through the earth, some would be going in one direction and the remainder in the opposite direction through the earth connection. It will readily be seen that, if such were actually the state of affairs, the laws above stated, that electricity only flows under a difference of potential and always flows when there is that difference, would be nullified.

Like everything else in the universe, the earth itself is always more or less electrified, and, as a consequence, it is always at a certain potential. It will therefore be seen that, were a body which had been electrified to a higher potential than the earth to be connected with the earth, a flow of electricity would take place passing from that body to the earth, so that both the body and earth assume the same potential, and it may be mentioned that the passage of this flow could be easily observed by the introduction of certain apparatus. On the other hand, were a body to be electrified to a potential lower than that of the earth and to be connected with it, a flow of electricity would be determined between the earth and the body, and the passage of this electricity could also be rendered evident. Consequently, when copper and zinc strips are immersed in acidulated water and the exposed ends become electrified, the one to a higher and the other to a lower potential than the earth, the connection of those extremities with the earth causes a flow of electricity from the plate of higher potential to the earth, and from the earth to the plate of lower potential. These flows will be equivalent to joining the plates directly together and so releasing the electrical stress.

Thus is it with every battery: the potential of the earth is above that of one end of the battery and below that of the other

end. There is then no need for a current to flow between the two earth-connections, and the assumption of such a state of affairs is quite gratuitous. It must not, however, be supposed that the flow of electricity from or to the earth can sensibly affect its charge or potential, the terrestrial charge as a whole being so enormous as to make any other charge incomparably feeble and insignificant. To make this clearer we will employ an analogy. Let us suppose that we have two tanks, one (A, fig. 4) containing water, and placed above the level of the ocean (C, D), the other (B) which we will suppose to be empty and partly immersed

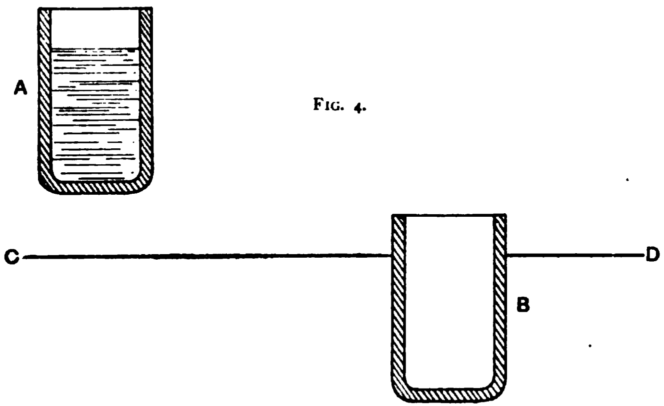


FIG. 4.

below the ocean level. If now we suppose holes to be made in the bottoms of the tanks, all the water will flow out of the higher tank into the sea below, while water will flow up into the lower one until the ocean level is reached. But of course no one would contend that these changes would make any difference in the level of the surrounding waters, even if more water were received from the higher tank than was given to the lower, and what is true in this case is equally true in the case of electricity. In fact, the earth is a body whose capacity for electricity, so far as we are concerned, is infinite, and nothing that we can do can alter its charge. The man who would assert that when he joins one end of his battery to earth, say, at London, and the other end to earth, say, at Aberdeen, and that in consequence a current flows through

the earth from one connection to the other, asserts, in fact, although he may not know the significance of his contention, that he places these two points in London and Aberdeen at different electrical potentials. He might as reasonably contend that if he turns on his water-tap into the Thames at London and digs a hole in the bank of the river at Windsor, he sets up a difference of level between the two places, and causes the water which he pours in at London to travel up against the stream and fall out at Windsor. It would also have to be conceded that when he reverses his battery connections, he at the same time makes the potential of, say, London, alternately higher and lower than that at, say, Aberdeen. In the special case, however, where a very heavy current is passing from the earth at one end of a line and to the earth at the other, the two earth connections being comparatively close together, as might happen in the case of an electric railway, it is of course possible for a considerable portion of the current to actually flow through the earth from one connection to the other, especially if the substratum be dry, and therefore a bad conductor. Manifestly this would be a very bad state of affairs, indicating that sufficiently good earth has not been made at the ends of the line, and that therefore a considerable amount of energy is being wasted.

We come now to a real difficulty—a solution of which is improbable, although it is, perhaps, in the future not impossible—and that is, to be able to say with certainty in which direction a current really travels, or, in other words, to declare which of two differently electrified bodies has the higher, and which the lower potential. All we can say with any certainty is that there is a difference of potential, and that therefore the current flows from the point of higher to that of lower potential. It is usual to assume, in the present incomplete and imperfect state of our knowledge concerning the nature and propagation of electricity, that the electric state which we know as positive has a higher potential than that state which we know as negative, whence we say, or assume, that electricity flows *from* a positively electrified *to* a negatively electrified body. And we will in this work follow this assumption, true or otherwise, as it involves no sacrifice of principles, notwithstanding the fact that experiments have been

performed which tend to show that that state which we call negative is really of higher potential than that which we call positive.

Reference has several times been made to the use of wire as a means of connection between two oppositely electrified bodies, or between two bodies at different potentials. Were we desirous of transmitting mechanical instead of electrical energy, a hempen or silken cord would answer equally well, if due provision had been made that the cord should have the requisite mechanical strength or tenacity to transmit the energy without fracture. But tenacity is not the necessary attribute for a body to possess in order that electricity may be readily propagated through it. All substances admit of this transmission, although to very varying degrees. A piece of copper wire offers greater facilities than a piece of iron wire of similar dimensions, which in turn offers greater facilities than a similar piece of German-silver wire. But the metals one and all are enormously superior in this respect to the great bulk of non-metallic substances. On the other hand, every substance, whatever its nature, offers a greater or less amount of resistance to the transmission of electricity. Bodies which offer little resistance to the electric flow are said to be good conductors, while those which offer considerable resistance are said to be bad conductors or insulators. To the former class belong the metals, carbon, ordinary water, &c., while the latter class includes such substances as glass, air, sulphur, resin, india-rubber, and ebonite. Between these two classes are many substances which might be included in either class, but no hard and fast line can be drawn.

It has been shown that the result of joining directly together two bodies electrified to different potentials is a flow of electricity from the body charged to the higher potential to that charged to the lower until electrical equilibrium between the two bodies is obtained. And a similar result follows if we join the bodies together by a piece of wire; while if they have only air or some other bad-conducting substance separating them, there will be no flow at all, or only a very feeble one. If in any given case the path of the flow is made longer, or more difficult, say by the interposition of a longer or poorer conductor, it naturally follows that the time which is taken for equilibrium to be restored is lengthened,

and the rate of restoration, that is, the strength of the current, is less. But if the potential difference and the quantity of electricity transferred are the same in the two cases, the energy expended in the effort to restore equilibrium is the same.

The result, then, of interposing a substance of poorer conducting power, or, what amounts to the same thing, of higher electrical resistance, between two bodies having a potential difference, is to reduce the strength of the flow or current passing from the one to the other. We can find a very simple analogy to this if we suppose two tanks at different heights one directly above the other, the lower one being empty and the upper one full of water. So long as the bottom of the higher one is intact the resistance to the flow of water from it to the other is practically infinite, but an effort to flow exists and takes the form of a pressure on the bottom of the tank, and if we interpose a relatively bad conductor of the water in the form of a very small pipe or tube between the tanks, there will be a correspondingly weak or feeble flow of water from the higher to the lower tank. If we increase the size or bore of the pipe, the conducting power will be increased proportionally, and a corresponding increase in the volume of the water (or in the strength of the current) flowing will be observed. Pursuing this to its finality, if the bottom of the upper tank is removed instantaneously there will result an equally instantaneous fall of the whole of the water in the tank. Such a state of things can easily be traced between two bodies charged to different electrical potentials or pressures and connected in turn by various substances whose conducting powers range from the almost infinitely great to the almost infinitely small; or, in other words, by varying the amount of resistance, which is here shown to be the converse or reciprocal of conductivity, we can, in a corresponding degree, vary the strength of the current.

To summarise our observations on the question of resistance, we may say that if we electrify two bodies, connected only by the air, to different potentials, we subject the intervening air to a species of stress. If we very considerably increase the potential, the air being no longer able to sustain the stress, a discharge or an electric flow ensues, in just the same way that we could force the bottom out of a tank of water and empty it by sufficiently

increasing the pressure. A similar result can be achieved, without increasing the potential difference, by reducing the distance between the electrified bodies, or by bridging over the air-space with a piece of wire or other good conductor. In either case the ability to sustain the stress is reduced, and we call this ability to sustain the stress resistance. The more resistance we insert between the electrified points or bodies, the more do we thereby reduce or prevent the flow of electricity from one to the other.

CHAPTER II.

PRACTICAL UNITS—OHM'S LAW—FUNDAMENTAL UNITS

In dealing, in the previous chapter, with the general attributes of electricity, the only degree of comparison arrived at was to say that one electrification, resistance, or current was greater or less than another. And to a somewhat considerable extent this was, until within the last few years, deemed sufficient. It is, however, now essential that more precision in comparing or measuring forces and their properties and effects should be obtained. Measurement is, in fact, the most important branch of electrical science, as, indeed, it is of every other physical science.

Instead of simply saying that one lump of iron is heavier or weightier than another, it is usual to say by how much they differ. Thus one lump may have a mass of ten pounds, and another a mass of twenty pounds. The latter is therefore ten pounds heavier than the former. We have here introduced a unit of measurement, viz. the pound, or unit of mass. Similarly, the inch or foot may be used as a unit of length, the second as a unit of time, the pint as a unit of capacity, the sovereign as a unit of coinage, and so on. These units are all such as everybody can readily appreciate. They are so frequently employed that no mental effort is required to understand what is meant when any one of them is mentioned.

In dealing with electricity the first thing we wish to measure is naturally the amount of the electrical difference between two bodies which causes an electrical stress and which may result in a current of electricity. But we are confronted with two difficulties. The first is that by none of the everyday units - by no unit employed for any other purpose - are we able to indicate exactly the electric potential of a body. Moreover, electricity being only a form of energy which induces or causes a certain condition of

matter, and not matter itself, it is impossible to measure it directly. We can only measure it by its effect upon material substances. In the next place, inasmuch as it is impossible to obtain or even to conceive of a body altogether devoid of electrification (although it is not always perceptible), it is impossible to fix on an absolute zero potential, and measure potentials from that point. In just the same way it is impracticable to have a zero level, some arbitrary point such as the sea-level at high tide having to be employed if we wish to measure the relative height of two or more points. It is, consequently, necessary to look elsewhere for a starting-point, and to fix on a convenient arbitrary potential zero. We take as a zero the potential of the earth's surface, and consider that bodies which are said to be positively electrified are at a higher potential than the earth, while negatively electrified bodies are at a lower potential. Positive and negative potentials may therefore be said to correspond to height and depth in their relation to the sea-level. Inasmuch, however, as we are unable to detect any potential at all unless we take two points or bodies whose potentials are different, the measurement of potential itself again presents difficulties. On the other hand, when we are called upon to measure the potentials of two bodies, what we really desire to know is the difference between those potentials ; or, if we call the potential of one body P, and that of the other P_1, we want to know the value of $P - P_1$; for, after all, it is this *difference* of potential that determines the flow of electricity. This difference of potential, which, when the conditions are favourable, is competent to develop and maintain a current of electricity, is known as electro-motive force, a term which is frequently contracted into the initials E.M.F., or, shorter still, into E. only. It is this electro-motive force, then, that we desire to measure, and the practical unit by which it is measured is known as the *volt.* We will, for the present, rest satisfied with the simple statement that the volt is approximately equal to, although actually a fraction less than, the electro-motive force of a single Daniell cell. (See Chapter III.)

Reference was made in the previous chapter to 'resistance,' and it was described as the converse of conductivity, which again we described as the ability of a body to transmit a current of electricity. It is easy to show that resistance may be expressed as a ratio

—the ratio of electro-motive force to current—and many authorities insist that it should always be regarded thus. It may also be expressed as a 'velocity,' or the ratio of length to time, but we prefer to deal with it as it appeals to practical electricians—viz. as an attribute of matter, varying with different substances, and in virtue of which such matter opposes or resists the passage of electricity, whence the current has to do 'work' or expend 'energy' in effecting the passage. The law of the conservation of energy teaches us that energy is indestructible, and it follows, therefore, that if energy has to be expended in impelling a flow of electricity against a greater or less amount of resistance, the equivalent of that energy must be developed in some other form. This other form is usually heat; or, in other words, when a body opposes a certain amount of resistance to the passage of electricity, heat is produced, the actual amount of heat being an exact counterpart of the energy expended in overcoming the resistance, and varying therefore directly as that resistance. Consequently, if we have two conductors, the resistance of one of which is twice that of the other, and if we send currents of equal strength through both wires, twice as much heat will be developed in the conductor of the higher resistance as will be developed in that offering the lower resistance. We shall have occasion to deal with this subject more fully in a future chapter, but we may add here, that if we wish to perform work at any point by means of an electric current conducted by a wire to that point, we must keep the resistance of that wire down to the lowest practical limit, because every fraction of the energy frittered away in heating the conductor means so much less energy available for the particular work which we wish the current to perform at the far end of the conductor. It is apparent, then, that we require a unit by which we shall be able to compare the resistances of various substances, and the unit selected is called the *ohm*. It was decided by an International Congress of Electricians which assembled in Paris in 1884 as being equal to the resistance which is offered to the flow of electricity by a column of mercury one square millimetre (the millimetre is equal to 0·03937 of an inch, or a small fraction less than $\frac{1}{25}$ of an inch) in section, and 106 centimetres long (the centimetre is equal to 0·3937 of an inch), the temperature being at the freezing point

(32° Fahrenheit or 0° Centigrade), and the pressure of the air equal to the pressure at the base of a column of mercury 30 inches, or 760 millimetres, in height. The Congress which determined the value of this unit also decided that it should be known as the 'legal' ohm, and it was understood to be but a provisional determination to remain in force until further and more exact experiment should decide the precise length of the column. At another Congress, held at Chicago in 1893, it was decided that the length of the mercury column should be 106·3 centimetres, and that the name of this unit should be the 'international' ohm; but this unit has not yet been adopted to any great extent, most people preferring to await further developments. A millionth part of an ohm is called a microhm, and one million ohms a megohm. The ohm is frequently indicated by the symbol ω, and the megohm by the symbol Ω; thus $15\,\omega$ means 15 ohms, and $4\,\Omega$ represents 4 megohms or 4 million ohms.

There have, in the past, been an almost unlimited number of units, more or less crude and unreliable; for it must be borne in mind that for a unit to be of any real value it must be permanent or durable, it must be susceptible of confirmation, and its derivation must be well known and invariable. One of the earlier units of resistance was that offered by a mile of the then best procurable iron wire of a certain gauge or diameter. The indefiniteness of such a unit may be conceived when it is called to mind that even now no two samples of wire can be obtained which will offer the same resistance; and still more so was this true a few years ago, when the quality of iron wire as a conductor was vastly inferior compared with what it now is, both as regards its actual resistance and its uniformity.

The only other unit which we need consider is that known as the B.A., or British Association, Unit. It was determined in London in 1863 by a committee appointed for the purpose by the British Association, and the method of determination then adopted was the basis upon which the Paris or legal ohm was afterwards calculated. These units are both based on what is called the C.G.S. system (p. 43), the Paris unit being really a correction of the B.A. unit. The practical standard of the former has, however, a great advantage over that of the latter, which

consisted of the resistance of a certain length of wire carefully preserved in London. This was, of course, rarely used, and duplicates of the standard had to be employed for comparing or standardising other resistances. The legal ohm is manifestly capable of being reproduced more easily, and it is this fact which imparts to it its chief value. There is the further advantage that the risk of change during the course of time in the nature, and therefore in the resistance, of any given standard wire is avoided. The B.A. unit is a fraction smaller than the Paris ohm, the actual proportion being 0·986 to 1·0. If it were possible at the present day to universally adopt a common unit, it would certainly be a great advantage, for then everybody would know what was meant when anybody else mentioned any particular resistance. But prior to 1884 a vast quantity of electrical apparatus and machinery was in use, and everything in England and certain other countries was measured by the B.A. unit, while the measurements employed on the Continent were for the most part referrible to the Siemens unit, which was the resistance of a column of mercury 1 metre (or 39·37 inches) long, the other details as to its size, temperature, and pressure being the same as those employed in devising the legal ohm. As it was, the various administrations and authorities were placed in a most unpleasant dilemma. If they re-standardised and re-marked all their then existing apparatus they would have had to incur enormous expense, while if they continued the use of their existing standards they would be perpetuating an inconvenience which they had called the Congress together to remove. In the majority of cases questions of finance compelled them to adopt the latter alternative, so that with us most apparatus continues to be measured by the B.A. unit, some of the apparatus employed in the newer industries, such as electric lighting, being measured by the legal ohm. It is probable that when the various authorities are assured that something approaching finality in the value of the unit has been attained much of the existing apparatus will be re standardised.

The student will frequently come across the expression 'specific resistance,' and it is a most important term. It may be defined as the resistance of any particular substance as compared with the

resistance of a piece of some other conductor, such as silver, both being of unit dimensions, and the test being made under similar conditions. It is a matter of great convenience that different bodies vary in their relative or specific resistances, for there are times when we want the lowest possible resistance, while at other times we require a large measure of resistance, more particularly when we desire to prevent an electric discharge, to prevent the flow of an electric current, or to prevent electricity leaking from one body to another. Appended is a table based upon that of Dr. Matthiessen, which shows the relative resistance of a number of metals frequently met with, and as the variation of the temperature of a body varies its electrical resistance, all the tests have been taken at a common temperature, viz. that of freezing point, or the necessary corrections made to correspond to that temperature.

TABLE SHOWING RELATIVE RESISTANCES OF CHEMICALLY PURE SUBSTANCES AT 0° C. IN LEGAL OR PARIS OHMS

Name of Metal	Relative Resistance	Resistance of a wire 1 foot long, 1/1000 of an inch in diameter	Resistance of a wire 1 metre long, 1 millimetre in diameter	Resistance in microhms	
				Cubic inch	Cubic centimetre
Silver, annealed	1·000	9·048	0·01916	0·5921	1·504
Copper, annealed	1·063	9·612	0·02034	0·6292	1·598
Silver, hard drawn	1·086	9·830	0·02080	0·6433	1·634
Copper, hard drawn	1·086	9·831	0·02081	0·6433	1·634
Gold, annealed	1·369	12·38	0·02620	0·8102	2·058
Gold, hard drawn	1·393	12·60	0·02668	0·8247	2·094
Aluminium, annealed	1·935	17·53	0·03710	1·147	2·912
Zinc, pressed	3·741	33·85	0·07163	2·215	5·626
Platinum, annealed	6·022	54·49	0·1153	3·565	9·057
Iron, annealed	6·460	58·45	0·1237	3·825	9·716
Lead, pressed	13·05	118·08	0·2498	7·728	19·63
German silver, hard or annealed	13·92	125·91	0·2666	8·240	20·93
Platinum-silver alloy (⅓ platinum, ⅔ silver) hard or annealed	16·21	146·70	0·3106	9·603	24·39
Mercury	62·73	572·30	1·211	37·15	94·32

The figures given in the right-hand column may be taken as representing the specific resistance of the various substances; they state in millionths of an ohm the resistance offered between two opposite faces of a cubic centimetre of each particular metal or alloy.

An alloy of copper, nickel, and zinc (the usual constituents of German silver), combined with 1 or 2 per cent. of tungsten, was introduced some years ago under the name of platinoid. It is found that the addition of tungsten imparts greater density to alloys and reduces any tendency to oxidation. When polished, the alloy is scarcely distinguishable in appearance from silver. A cubic centimetre offers between opposite faces a resistance ranging from about 30 to 36 microhms, so that its resistance is about one and a half times that of German silver. As, however, alloys always vary more or less in their composition, a definite resistance cannot safely be assigned to any commercial variety, and calculations concerning them can only be accepted as actually true of the particular samples tested. Platinoid, when drawn hard, is, like copper, softened by heating and sudden cooling.

The admixture of even a minute proportion of foreign matter very considerably reduces the conductivity or increases the resistance of a metal. A very remarkable effect is observed when an alloy of two or more metals is tested, for the specific or relative resistance of the alloy will always be found higher than that of either of its constituents. Purity in the case of simple substance, and absolute uniformity in the constitution of alloys, such as German silver, is, therefore, pre-eminently essential, if the highest conductivity or if a certain specific resistance is desired, as is shown by the following table, giving the relative conductivities of various samples of copper.

TABLE SHOWING THE COMPARATIVE CONDUCTIVITY OF PURE COPPER AND THE BAR COPPER OF COMMERCE [1]

(*All the wires were annealed*)

	Conducting power
Pure copper	100·0 at 15·5° C.
Lake Superior, native, not fused	98·8 at 15·5° C.
Ditto, fused, as it comes in commerce	92·6 at 15·0° C.
Burra Burra	88·7 at 14·0° C.
Best selected	81·3 at 14·2° C.
Bright copper wire	72·2 at 15·7° C.
Tough copper	71·0 at 17·3° C.
Demidoff	59·3 at 12·7° C.
Rio Tinto	14·2 at 14·8° C.

[1] Report of the Government Submarine Cable Committee.

Or again, if the relative conductivity of pure copper is taken as 100, then that of copper mixed with 1·6 per cent. in volume of silver will be only 65; while the conductivity of silver mixed with 1·2 per cent. in volume of gold will be 59 when that of pure silver is taken as 100.

A highly interesting phenomenon is the wonderful effect which a variation in temperature produces upon the resistance of the various substances through which a current may flow. The effect would be less surprising were it general, or were it consistently uniform in all bodies, but the great feature to be observed is that while in the case of metals the resistance of a conductor invariably increases with an exaltation in temperature, the non-metals all show a decrease in resistance under similar circumstances. It is also a remarkable feature that in the case of metals the variation is much less in alloys than in pure metals. These results are fraught with the greatest importance, as they limit considerably the number of substances available for many classes of electrical apparatus. For example, wires which are to be employed as standards for comparing or measuring resistances should have as nearly as possible the same value at all temperatures. It may be observed that the insulating coatings of the wires in the telegraph cables laid in such waters as the Indian Ocean show a marked decrease in their insulating properties after submergence, consequent upon the fact that the water is several degrees warmer than that in the tanks in which the standardising tests were made. The accompanying table, showing the percentage variation in the resistance of various bodies between the temperature of freezing water and that of boiling water, should prove eminently interesting. It is certainly useful and important.

As may have been gathered from what has already been said, when we increase the length of a conductor we invariably increase its resistance. This follows as a matter of course from the fact that if we urge a certain current through a wire of increased length, we give it more work to do, necessitating, consequently, a greater expenditure of energy in precisely the same way that a railway engine would consume more coal in taking a train a distance of 200 miles than it would consume in taking it only half that distance. The resistance of a conductor of uniform material and

Name of Metal	Conducting power at 0° C. Silver = 100	Percentage fall of conducting power between 0° and 100° C.
Pure iron	16·81	39·2
Pure thallium	9·16	31·4
Other pure metals in a solid state	—	29·3
Gold with 15 p.c. iron	2·76	27·9
Proof gold	72·55	26·4
Standard silver	80·63	23·2
Gun metal (Austrian)	27·08	18·3
Copper with 25 p.c. platinum	22·08	11·5
Silver with 5 p.c. platinum	31·64	11·3
Silver with 9·8 p.c. platinum	18·04	7·1
Copper with 9·7 p.c. tin	12·19	6·6
Gold-silver alloy	15·03	6·5
Platinum with 33·4 p.c. iridium	4·54	5·9
German silver	7·80	4·4
Gold with 4·7 p.c. iron	2·37	3·8
Silver with 25 p.c. palladium	8·52	3·4
Silver with 33·4 p.c. platinum	6·70	3·1
Platinoid	—	2·09

thickness or cross-section varies directly as its length—that is to say, if we vary the length of the conductor we vary its resistance at exactly the same rate, or, in fewer words, resistance varies directly as the length of the conductor. If a mile of wire of a certain gauge offers a resistance of ten ohms, two miles of the same wire would offer twenty ohms.

The effect of increasing the size or sectional area of a conductor is to increase its conductivity and, consequently, to diminish its resistance, in exactly the same way that increasing the diameter of a pipe increases the amount of gas or water that can be passed through it. The resistance of a conductor varies inversely as its sectional area. That is, if we have two conductors, such as two specimens of copper wire, drawn from the same bar, the amount of resistance which the wires will offer depends upon the size of the wires or on the area of the ends exposed on cleanly cutting them at right angles to their length—that is to say, upon the amount of metal through which the current can flow. Most wires are round, so that the section is a circle, and it becomes necessary to understand the method of comparing the areas of circles. The area of a circle varies as the square of its diameter; for example,

if we have two circles, one having a diameter of one-tenth of an inch and the other of two tenths of an inch, their areas or the spaces they enclose will not be in the proportion 1 : 2, but as the squares of those figures, viz. 1 : 4, so that one wire which is twice the diameter of another, other things being the same, only offers one quarter of the resistance offered by the thinner wire. While if we treble the diameter of the wire, or make it three-tenths of an inch, the resistance will be only one-ninth of that of the thinnest wire. As a matter of fact, the thickest of these three wires will weigh exactly nine times as much as the thinnest, there being nine times as much metal in it. We may, therefore, state our law in other words by saying that the resistance of wires uniform in all particulars excepting thickness varies inversely as their weight. Thus, if a mile of copper wire weighs 100 lbs. and has a resistance of 9 ohms and an equal length of similar copper wire weighs 150 lbs. the resistance of the latter will be 6 ohms. Again, the specific resistances of iron and copper are approximately as 6 to 1. If, now, a mile of iron wire, 0·240 of an inch in diameter, has a resistance of 5 ohms, and it is thought for certain reasons desirable to substitute a mile of copper wire having the same resistance, we should have to use wire weighing one-sixth the weight of, or whose sectional area would be one-sixth of, that of a copper wire 0·240 of an inch in diameter, because the resistance of a mile of the latter would be only five-sixths of an ohm. The required thickness could be ascertained by rule of three, for if x stands for the required diameter,

$$6 : 1 :: (0{\cdot}240)^2 : x^2,$$

from which we find $x^2 = 0{\cdot}0096$. Therefore x, or the required diameter, is equal to the square root of 0·0096, or 0·098 of an inch nearly.

A conductor offers to the passage of electricity, at a given temperature, a constant resistance which is altogether independent either of the electro-motive force or of the strength of the current. That is to say, a wire which offers 10 ohms to the passage of a feeble current, offers precisely the same resistance to a powerful current, except in so far as an increase in the strength of the current involves a corresponding increase in the temperature of the wire,

and this increased temperature causes a proportionately increased resistance, as already pointed out.

We come now to the consideration of the laws which determine the strength of a current and of the relationship subsisting between strength and the other attributes of an electric current. The real relationship can, perhaps, be best understood by the aid of a simile. Let us suppose two tanks, one very high up, say a hundred feet above the ground, the other raised only a few feet. Let both tanks contain the same quantity of water, and let both of them be supplied with pipes, the one for the upper tank being, however, very much smaller in diameter than that for the lower. On turning the taps the water from the upper tank will issue forth with much greater force than that from the lower tank, although the quantity or rate of flow from the lower tank may considerably exceed that from the upper tank. In other words, the pressure in the long small pipe is much greater than in the short but large one, while the quantity of water delivered by the former is considerably less than that delivered by the latter. Pressure in the case of a column of water corresponds with the electro-motive force of a battery, while the volume or quantity of water flowing through the pipe corresponds to current strength. But to pursue the analogy still farther, if the upper tank be raised sufficiently high, the greater pressure so obtained will augment the velocity of the water, and the two tanks will be emptied in the same time. There are two things, then, that govern the quantity of water delivered or the rate of delivery—viz. the pressure, and the size of the pipe, which latter corresponds in electrical considerations with the size of the conductor and consequently with the resistance.

By current strength is meant, therefore, *the rate of flow of electricity, and it is measured by the quantity of electricity passing any point in a circuit during a given time.* It corresponds to the rate of delivery of gas or water by a pipe. In a simple circuit it depends upon two things, the electro-motive force of the generator or battery and the resistance of the whole circuit, which comprises the wire and apparatus as well as the battery itself. The practical unit of current strength or rate of delivery is called the *ampere*, and is that strength of current which is developed in a circuit of one ohm resistance by an electro-motive force of one volt. If

this current is maintained for one second, one unit of electrical *quantity* is delivered and this unit is called the *coulomb*. If a current of half an ampere flows for two seconds, the quantity of electricity delivered is again one coulomb. So also is it if a current of two amperes flows for half a second, so that in every case the rate of flow, or current strength in amperes multiplied into the time in seconds, gives us the total quantity of electricity or the number of coulombs. Thus if Q represents the quantity of electricity in coulombs, C the current strength in amperes, and t the time in seconds,

$$Q = C \times t.$$

As the quantity of electricity delivered is rarely required to be known, but rather the rate of delivery or flowing, we will deal more fully with the method of ascertaining this rate. In order that this matter may be more readily understood, we will at once proceed to the discussion of 'Ohm's Law,' which declares that *the current strength varies directly as the electro-motive force, and inversely as the resistance.* This law may be represented by the simple equation—

$$\frac{\text{Electro-motive force}}{\text{Resistance}} = \text{Current strength},$$

or,

$$\frac{E}{R} = C.$$

As an example of the relation which the units bear to each other, we may take the simple case of a battery having an electro-motive force of one volt and sending a current through a circuit whose total resistance is one ohm. The current strength will then be one ampere, thus :—

$$\frac{1 \text{ volt}}{1 \text{ ohm}} = 1 \text{ ampere},$$

and if this current is maintained for one second, one coulomb of electricity will have passed. By doubling the resistance, we get

$$\frac{1 \text{ volt}}{2 \text{ ohms}} = 0{\cdot}5 \text{ ampere}.$$

Similarly, by doubling the electro motive force we get, with unit resistance,

$$\frac{2 \text{ volts}}{1 \text{ ohm}} = 2 \text{ amperes}.$$

A little reflection will make evident the subsidiary law that *the current strength is the same in all parts of the circuit*, and does not in any sense vary in different parts of the same circuit. The current strength can easily be supposed to be uniform in a uniform conductor, but if we make up a circuit with wires of different degrees of conductivity, or if we interpose any liquid conductor, the same law holds good, just as would be the case if we were to urge a current of water through a pipe of variable diameter. It is manifest that if a gallon of water enters the pipe in a certain time, the same volume must pass out in the same time (supposing the pipe to have been already full), and the same volume must pass every point in the pipe in the same interval of time, although in the thinner or smaller portions of the pipe the water travels faster and generates a little more heat by friction with the sides of the pipe than in the larger sections of it. This latter analogy also holds good with regard to electricity, for in the thinner wire or poorer conductor more heat will be developed than in the thicker or better conductor. It is this fact that makes electric lighting by incandescent lamps possible. It is doubtful whether in the whole range or history of electrical science a law has ever been enunciated so full of truth and of such immense importance as that discovered by George Simon Ohm, and we shall find frequent need to refer to it in the succeeding chapters.

For the benefit of those, and our experience teaches us that they are very numerous, who do not understand the full meaning of a simple equation, we may say that if

$$\frac{E}{R} = C, \text{ then } \frac{E}{C} = R, \text{ and}$$

$$E = RC \text{ (or } R \times C).$$

So that, if, of these three quantities, we are told two, we can always readily calculate the third. Thus, with a current of two amperes and an electro-motive force of 10 volts, the resistance will be

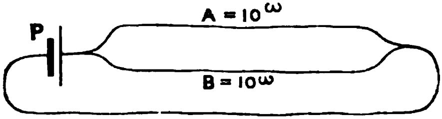
$$\frac{10}{2} = 5 \text{ ohms.}$$

Similarly, if a current of 5 amperes flows through a resistance of 10 ohms, the electro-motive force capable of maintaining this current will be

$$10 \times 5 = 50 \text{ volts.}$$

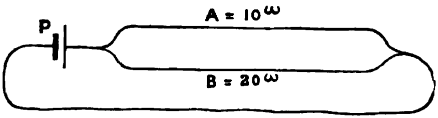
When two or more channels or paths are open to a current of electricity, the current divides between them, just as water or gas in a pipe will divide into any number of branch pipes. If in the case of electrical conductors there are two wires (A and B, fig. 5), between which the current can divide, and if

FIG. 5.



the resistances of the two wires are equal, the current will divide equally between them ; thus, if a current of two amperes flows from the battery P, one ampere will go through each wire, the two currents re-uniting at the junction and returning to the battery by the common wire. When the resistances are not equal, the current will divide inversely as the resistances ; thus, if the resist-

FIG. 6.



ance of one wire (A, fig. 6) is 10 ohms, and of another (B) is 20 ohms, and a current of three amperes divides between them, two amperes will go through the wire A of 10 ohms and one ampere through the wire B of 20 ohms.

When two or more wires are joined together so that the current divides between them, they are said to be joined up in 'parallel,' and when the end of one is joined to the end of another so that the whole current goes through both wires, one after the other, the wires are said to be joined up in 'series.'

The law for two conductors holds equally good for a larger number. Thus, if there are 10 wires of uniform resistance and a current of 10 amperes divides between them, it will do so equally, so that one ampere will flow through each wire. When the resistances vary, then the current flowing through each wire will vary also, but in the inverse ratio.

When, however, two or more wires are joined up in parallel, a serious alteration is made in the condition of the circuit, for the total amount of current that is produced, whether it be from a primary battery, a dynamo-electric machine, or any other source of electrical energy, will be increased. This increase follows from the fact that when wires are joined up in parallel, their united, or, technically speaking, their joint resistance is less than that of any one of the wires taken separately. The meaning of this will be more readily apparent if a wire is regarded as a conductor rather than as a source of resistance. Thus, if two equal wires lie side by side and the current is allowed to flow through them, the conducting power of the double wire will be twice that of either wire taken separately, in precisely the same way that a water or gas-pipe two square inches in section will transmit twice as much as a similar pipe only one square inch in section. If, therefore, the conductivity of the two wires in parallel is twice that of one of them, their united or joint resistance will be only half that of one of them. Thus, if two wires, each of 100 ohms resistance, are joined to a battery in parallel, their joint resistance will be 50 ohms. Similarly, if ten wires, each of 100 ohms resistance, are joined in parallel, they will offer a joint resistance of 10 ohms. We can, therefore, say that if any number of wires (n) of uniform resistance (R) are joined in parallel, or 'multiple arc,' as the arrangement is sometimes called, then their joint resistance $= \frac{R}{n}$. Suppose, now, that our battery has an electro-motive force of 100 volts, and that its internal resistance is negligibly low; with one wire of 100 ohms joined on we get—

$$\frac{100 \text{ volts}}{100 \text{ ohms}} = 1 \text{ ampere.}$$

With two such wires we get—

$$\frac{100 \text{ volts}}{\frac{100}{2} \text{ohms}} = \frac{100}{50} = 2 \text{ amperes.}$$

This current divides equally between the two wires, one ampere going through each.

With ten wires we get—

$$\frac{100 \text{ volts}}{\frac{100}{10} \text{ ohms}} = \frac{100}{10} = 10 \text{ amperes.}$$

Whence one ampere will still go through each wire, so that the strength of the current increases in precisely the same proportion as the number of wires. If, however, the internal resistance of the battery is proportionally high enough to necessitate its being taken into account, the reduction of the external resistance will not produce so marked an effect. With a battery resistance of 100 ohms and a single wire of a like resistance we get

$$\frac{100}{100 + 100} = \frac{100}{200} = 0{\cdot}5 \text{ ampere,}$$

and when two wires are joined in parallel we get—

$$\frac{100}{100 + \frac{100}{2}} = \frac{100}{150} = 0{\cdot}66 \text{ ampere.}$$

With ten wires we get—

$$\frac{100}{100 + \frac{100}{10}} = \frac{100}{110} = 0{\cdot}90 \text{ ampere.}$$

Thus with two wires in parallel a current of 0·33 ampere would flow through each wire, while with ten wires the current strength in each wire would be only 0·09 ampere.

When the parallel circuits are of different resistance, the calculation of their joint resistance involves a little more trouble. Let us suppose two wires joined in parallel, their individual resistances being R_1 and R_2 respectively. As we have already pointed out, resistance is the converse of conductivity. Therefore, R_1 and R_2 representing the resistances, $\frac{1}{R_1}$ and $\frac{1}{R_2}$ will represent their conductivities, whence the united conductivity will be $\frac{1}{R_1} + \frac{1}{R_2}$, which is equal to $\frac{R_1 + R_2}{R_1 R_2}$. This being the joint conductivity, the joint

resistance will be the converse of this, viz., $\frac{R_1 R_2}{R_1 + R_2}$; thus, if $R_1 = 500$ ohms and $R_2 = 1{,}000$ ohms, their joint resistance will be

$$\frac{500 \times 1000}{500 + 1000} = \frac{500{,}000}{1{,}500} = 333 \cdot 3 \text{ ohms.}$$

Briefly put, it may be said that the joint resistance of any two conductors is equal to the product of those resistances, divided by their sum.

Similarly with three (or more) wires of different resistances, their joint conductivity would be

$$\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} = \frac{R_1 R_2 + R_2 R_3 + R_1 R_3}{R_1 R_2 R_3},$$

whence the joint resistance will be

$$\frac{R_1 R_2 R_3}{R_1 R_2 + R_2 R_3 + R_1 R_3}.$$

If R_1, R_2, and R_3 are 500, 1,000, and 2,000 ohms respectively, their joint resistance will therefore be

$$\frac{500 \times 1{,}000 \times 2{,}000}{(500 \times 1{,}000) + (1{,}000 \times 2{,}000) + (500 \times 2{,}000)}$$

$$= \frac{1{,}000{,}000{,}000}{3{,}500{,}000} = 285 \cdot 7 \text{ ohms.}$$

In the process of electrical testing it is frequently found to be necessary to employ wires of various resistances, either as standards for comparison, or simply for the purpose of placing in a circuit and varying the strength of the current therein. The wires are usually coiled up or wound on bobbins, so as to occupy little space, and are then placed in a convenient case or box; such a set of coils is known as a resistance-box, or rheostat. But if the coils are to be of any real value as standards, great care must be exercised, not only in accurately measuring their resistance, but also in selecting the materials of which they are made, so as to avoid deterioration or change of any kind. The wire must be completely covered throughout by some good insulating substance, to prevent contact between adjacent convolutions, and the material used for this purpose must be able to withstand without

change the highest temperature to which it is likely to be subjected ; and it must also be incapable of producing any injurious action on the wire. The best insulating material for such resistance coils is silk thread, which is wound spirally over the wire in one or two layers. The metal employed for the conductor must be free from any liability to oxidation. Another important matter for consideration is the amount of its variation in resistance, with a given change of temperature.

In very important work it is necessary to know the temperature at which a coil was originally measured, and either bring it to that same temperature during the experiment or else make a correction in the result. But either course is somewhat tedious, and in ordinary cases impracticable. In practice the coils are measured at the temperature at which it is probable they will generally be used, say 15° C. (59° F.), and the error lessened by choosing a metal whose percentage of resistance variation with change of temperature is very low.

In addition to changing with any alteration in the temperature of the atmosphere, the wire is more or less heated by the passage of a current itself, so that its resistance may easily alter during even a brief or rapidly performed test or experiment. An examination of the table given on page 22 shows the variation of a platinum-silver alloy to be very small, and this alloy is therefore very extensively employed in high-class apparatus, where the expense becomes a matter of minor importance.

For coils of high resistance it is necessary to choose a metal whose specific resistance is high ; otherwise the length of wire would probably be inconveniently great. For low resistances, however, this is not so important ; in fact, if a metal of high specific resistance is then used, the wire must be comparatively thick, otherwise it would be so short that very great difficulty would be experienced in making the coils of exactly the right resistance, because a considerable difference would be caused by a small error in the length of the wire. In all cases, however, there is the great advantage in the case of a thick wire, that a given amount of heat raises its temperature to a less extent than it would a thinner wire.

Copper is unsuitable for resistance coils on account of its

great variation in resistance under a variation of temperature; and, as its specific resistance is low, it would be necessary to employ either a very long or a very fine wire to make a coil of high resistance.

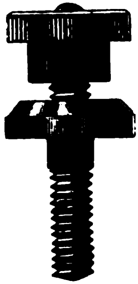
Taking into consideration cost, durability, high specific resistance, and low temperature error, German silver is undoubtedly the most useful material for the purpose; and it is consequently used more frequently than anything else.

A single resistance coil—such, for example, as a standard coil, or one designed for some other special purpose—is, after having been carefully wound on an ebonite or boxwood bobbin, usually mounted in a wooden case or box, furnished with an ebonite cover. Two brass blocks or plates, to which the ends of the wire are soldered, are screwed on to the under side of this cover. Connection with the external circuit is made by means of terminals fixed on the top of the case, and connected electrically with the plates underneath. The form of terminal employed is a matter of more importance than it is usually considered to be, for the contact surfaces at the junction of two conductors, or two parts of the same conductor, always offer some resistance, and if these surfaces are oxidised or dirty, or if the contact is not firm, this resistance will probably be considerable. It is for this reason that the form of terminal or binding-screw shown in fig. 7 is open to serious objection, the contact being as a rule uncertain. Such terminals, in which dependence for good contact has really to be made upon the end of a screw (frequently pointed as if to accentuate the evil), should be eschewed, at least for small wires or such as can be readily bent with the fingers. A much better and more reliable terminal is that shown in fig. 8, where the wire is clamped between a fixed base and a screw nut. In tightening the nut, a rubbing effect is produced, which assists in removing any superficial dirt either on the wire or on the terminal, and so tends to ensure good and steady contact. When using this terminal the wire should be bent round the screw shaft, and not simply gripped upon one side of it, otherwise there will, in tightening up, be a risk of bending the shaft. With the large wires used in electric lighting it is inconvenient and sometimes impracticable to bend the wire. In that case the first-mentioned type of terminal, fig. 7, or a modifi-

cation of it, is resorted to. In the case of 'stranded' conductors special terminals are required, and a further reference to these will be found in the closing chapter.

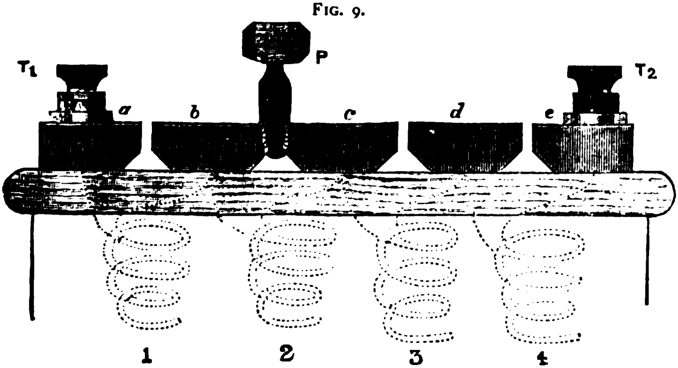
FIG. 7.

FIG. 8.



As it more generally happens that a number of coils are required to be so put together that the resistance to be introduced into any particular circuit can be varied at will from zero to the maximum, special devices have to be employed to obtain this

FIG. 9.



result with the smallest possible waste of time. Fig. 9 shows the best method of casing a number of coils of various resistances; all the coils are joined in series, and the junction of each pair is soldered to the bottom of a brass block, as shown in the figure,

or to a pin projecting from the under side of the block. Great care is taken in winding to ensure the absence of contact or leakage between one portion of the wire and another. The bobbins are fixed to the under side of the ebonite top of the case, the wires being connected to the brass blocks *a*, *b*, *c*, *d*, *e*, which are firmly fixed to the upper side of the ebonite, the adjacent ends of the various blocks being turned out to receive a slightly tapered or conical brass plug. The end blocks are fitted with terminal screws, T_1 and T_2, to which any external wires can be connected. Now, if a wire leading from the copper pole of a battery is joined to a terminal, T_1, and another from the zinc pole to T_2, a current will flow through the coils in the resistance box, starting from the left-hand block *a* and passing through the resistance coil No. 1 to the second brass block *b*. Here it has two paths open to it; one through the coil No. 2, of comparatively high resistance, the other through the brass plug P, which has, practically, no resistance at all. All the current will therefore pass by the latter path, and none through the coil, which is said under these circumstances to be 'short-circuited' by the plug P. The current must pass through the coils 3 and 4 before it reaches the terminal T_2. The total resistance interposed in the current by means of the resistance box will therefore be $1+3+4=8$ ohms.

The brass plug, which should be furnished with an ebonite cap or top, must be carefully tapered to fit the hole *exactly*. Should there be the slightest shake, or should there be any dirt or grit on the blocks or on the plug itself, the contact will be uncertain and the resistance variable. When properly made, the plug, on being inserted with a little pressure and a slight twist—say to the right—should fit so thoroughly that on raising it the resistance box should be lifted with it. The pressure applied should not be excessive, otherwise there will be some risk ot distorting the cover of the box. Many cases have occurred where so great a pressure has been applied that a permanent distortion has been produced, and the proper fitting of the plug rendered impossible. The plug should not be made so long that it can butt against the ebonite at the bottom of the hole, and should the plug in course of time wear so much that it does touch the bottom, the end should be carefully filed off. To remove the plug it

should be necessary to first loosen it by giving a slight twist to the left. The lower and the two vertical edges or corners of the blocks should be filed away, as shown in fig. 9, to give a larger ebonite insulating surface between the blocks and to allow this surface to be kept clean. This arrangement is necessary in order to prevent, as far as possible, any short-circuit being caused by the accumulation of dust and dirt.

Resistance coils fitted in this way can easily be put in or taken out of the circuit, by withdrawing or inserting plugs between the brass blocks to which the ends of the various coils are soldered. It is hardly necessary to remark that the surfaces of contact should not be lacquered, but should be kept bright and clean. The slight twisting recommended above in inserting a plug serves the further useful purpose of keeping the contact surfaces clean.

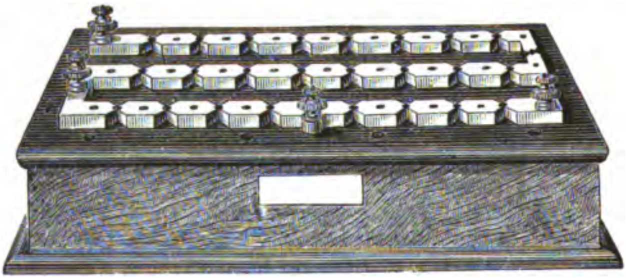
Resistance coils are frequently used in conjunction with and in the immediate vicinity of delicate measuring apparatus in which a sensitive magnetised needle is employed. If, in such cases, the coils are wound continuously on the bobbin, or in the same manner as a solenoid, an 'electro-magnetic field' will be set up immediately a current is sent through the coils, which may be sufficiently strong to impart motion to the needle. If the instrument is being employed to measure either the current passing through the resistance, or any effect of that current, serious errors may therefore be introduced by the direct effect of the coils upon the needle. Again, as we shall see later on, it is impossible to start or stop a current in a solenoid suddenly, because work is done and time occupied in establishing, and again in disestablishing, the electro-magnetic field. These are serious defects, and it is fortunate, therefore, that the remedy is simple.

To obviate the difficulty it is only necessary that the wire should be wound 'double'—that is to say, the required length should be measured off and then doubled in the middle, the two halves being wound on together. The meaning of this will perhaps be more apparent on referring to the illustration (fig. 9). The double winding is more easily managed, especially with long coils, by winding the two halves off two separate spools or bobbins and soldering the inner ends together. In either case the two extremities of each coil are brought out together. We have thus

two similar helices carrying currents equal in strength but opposite in direction, and the consequence is that the disturbing effect which would be produced by one helix is exactly counteracted or neutralised by the opposite effect which would be due to the other.

When the coils to be enclosed in a box are numerous, it is inconvenient to place them in one long row and thus make a long narrow box. It is preferable to arrange them in two, three, or more parallel rows, connecting these rows together by brass blocks and plugs, as indicated in fig. 10. The centre of each block may also be provided with a tapered hole of the same size as those between the blocks, in order that the plugs may be placed in them when not in use for short-circuiting the coils. It is most

FIG. 10.



important that all the holes and all the plugs should be of exactly the same dimensions, so that the plugs may be interchangeable, or that any one plug may be used for any of the holes. Failing this, considerable inconvenience and risk of error would speedily ensue, for then there would be a particular plug for each hole, and very great difficulty would be experienced in using them and keeping them in their proper places.

Another very useful form of resistance-box or rheostat is shown in fig. 11. The coils are placed inside a round brass case or box provided with an ebonite top and mounted on a mahogany base. Ten coils, each of 40 ohms resistance, are connected to eleven rounded steel points projecting through the ebonite top of the instrument. Ten other coils, each of 400 ohms resistance, are connected to the steel points on the other half of the top

side of the ebonite. Three more coils are connected to the brass blocks fixed on the base of the instrument ; when not required the last-mentioned coils are short-circuited by the usual brass plugs. Supposing the current to enter by the right-hand terminal, it will pass to the nearest brass block, then through the coils of 4,000, 20, and 10 ohms (or through such plugs as may be inserted between the respective blocks), to the brass block nearest to the left-hand terminal. It then passes

FIG. 11.

by a piece of insulated wire under or in the base of the instrument to the zero stud on the right-hand side, whence it will pass through the 40-ohm coils until it reaches the steel spring carried by the front brass arm, which is movable over these coils and studs. Passing along this arm, which is metallic throughout, it will enter the other movable arm and thence pass to the 400-ohm coils. Leaving at the zero stud of these 400-ohm coils on the left-hand side, it will pass by a thick wire direct to the left-hand terminal and so to the other part of the circuit. The two arms can be readily moved round over the steel studs or points, so that the range of one arm is from 0 to 400 ohms, and that of the other from 0 to 4,000 ohms. The total resistance in circuit with the arms as shown, and all three plugs *in*, is 3,880 ohms.

The total range of the instruments is from 10, by multiples of 10, up to 8,430 ohms. Although it is a great advantage that the resistance can be very readily varied, the instrument is somewhat objectionable for delicate measuring purposes, as the contact springs are apt to get weak and the contact unreliable, the resistance then becoming variable.

Another method of casing and joining up resistance coils is shown in figs. 12 and 13. A (fig. 12) is a circular brass plate; *b*, *c*, *d* are brass blocks. A tapered hole is provided between each of these outer blocks and the plate A for the usual conical plug.

FIG. 12.

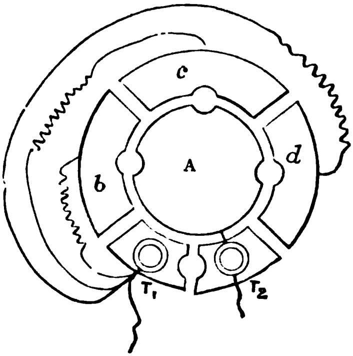


FIG. 13.

T_1 T_2 are the terminal screws, the latter of which is permanently connected to the brass plate A. One end of each of the three coils is soldered to terminal T_1, and the other end of each to one or other of the outer brass blocks. When it is desired to *insert* in the circuit one of the resistance coils, the plug is placed in the hole which is between the block connected to that coil and the plate A. Thus the action is the reverse of that previously described, for here we insert a plug to insert resistance, removing it to cut out the resistance. Only one coil can, however, be used at a time; and if the plug is placed between terminals T_1 and T_2 the whole box is short-circuited. Fig. 13 shows a box of coils connected according to this method. It is designed for use with a galvanometer as a set of 'shunt coils,' having respectively $\frac{1}{9}$, $\frac{1}{99}$, and $\frac{1}{999}$ of the resistance of the galvanometer with which it

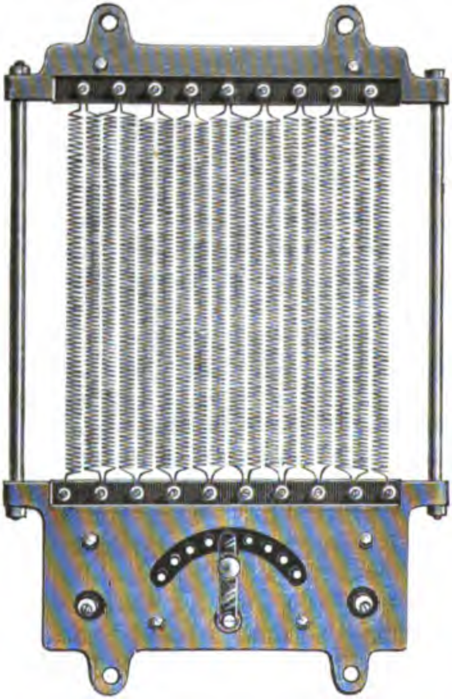
is intended to be used. (The nature and applicability of shunt coils will be dealt with in Chapter IV.)

For general use as well as for accurate measurements, the form of resistance-box shown in figs. 9 and 10 should be used. But where a means of rapidly varying the resistance is necessary, the form shown in fig. 11 is often employed. As we have already remarked, resistance varies considerably with temperature, whence every set of coils should have marked on the case the temperature at which they were measured. Then for very accurate tests they may either be brought to that temperature or a correction made in the reading, but in any case it is known whether any great error is likely to be caused by using them at any particular temperature. In the case of the coils shown in fig. 13, copper wire is employed because the galvanometer coils are of copper, and it is essential that the shunt coils should vary in resistance exactly with the galvanometer coils, in order that the ratio between the two may remain constant.

It sometimes happens, however, that sets of resistance coils are required merely for the purpose of dissipating a certain amount of electrical energy. For instance, it becomes necessary, when employing some dynamo-electric machines, to reduce the electrical output in response to a correspondingly reduced demand made upon it by the external circuit; and this can be done by joining extra resistance in series with the magnet coils, and allowing some of the power to be expended in heating this extra resistance. In such cases it is not necessary to know exactly the value of the resistance in ohms, but it must be divided into a number of small and approximately uniform sections, so that its value can be changed gradually. As the currents employed are, in such cases, very strong, it is important that the coils should be able to withstand a considerable rise in temperature without being in any way injured. The wire must therefore be left bare, so that the heat generated can be dissipated by radiation and convection. Were the wire to be covered with any insulating material, the dissipation by both these processes would be impeded, and there would be the further disadvantage that this sheathing would sooner or later be damaged, if not destroyed. The wire should be of a metal which has a fairly high specific resistance and fusing point, and

should not be liable to deterioration by combining with atmospheric oxygen. For these reasons, German silver and tinned or galvanised iron are usually employed, but in special cases platinoid is resorted to. It is essential to select for the supporting frame a material which, while strong, is also non-inflammable and a good

FIG. 14.



insulator, with the smallest possible power of condensing atmospheric moisture upon its surface. In fig. 14 is shown such a set of resistances, suitable for carrying very heavy currents. There are two cast-iron end frames, which are hollow and have slate slabs fitted into them, these slabs being held in position by bolts which pass through both the slate and iron frame. The slabs, projecting inwards from the frames, carry a series of brass bolts and nuts, on to which are fixed the ends of spirals of bare

German-silver wire. Slate is an effective insulator for the purpose, and the device of passing the connecting bolts right through it and securing them with nuts, instead of trusting to a screw-thread cut in the material, renders it mechanically satisfactory. The frame is completed and made rigid by a pair of iron rods which are secured to the cast-iron ends. The whole of the spirals are joined in series, the terminals for connection to the external circuit being fixed on to the slate through holes in the bottom end-frame. The left-hand terminal is joined to the bottom of the left-hand spiral, while the right-hand terminal is connected to the lever of a switch which passes over nine contact pillars rising from the slate bed through an opening in the frame. These pillars are connected to the lower junctions of the spirals, and by altering the position of the switch the spirals can be cut in or out of circuit, in pairs, as desired. A set of resistances similar to that illustrated is capable of dissipating about 1,000 watts without undue heating.

We have seen that whenever a current of electricity flows, a certain amount of energy is expended; and it is necessary to be able to measure exactly the amount of energy so expended in any circuit or in any part thereof. The quantity of work performed in raising a mass of one pound through a difference of level of one foot against the force of gravity, is generally taken as the unit of mechanical energy and is known as the foot-pound. The work done in raising any mass through any height, is found by simply multiplying together the number of pounds in that mass by the number of feet through which it is lifted. Somewhat similarly we can take as the practical unit of electrical energy, the amount expended in transferring a unit quantity of electricity (one coulomb) under a difference of potential of one volt. And by multiplying the number of coulombs which have flowed from one point to another by the difference of potential in volts between those points, we obtain the number of units of electrical energy expended during the passage of the current. The unit of electrical energy, or one coulomb multiplied by one volt, is called the *joule*. As a simple numerical example we may suppose a current of 10 amperes to flow for 5 seconds, then the quantity of electricity passing through the circuit would be 50 coulombs, and if this current

were maintained by a potential difference of 8 volts, the amount of energy expended in that time would be $8 \times 50 = 400$ joules.

As a rule, we wish to know the *rate* at which work is being done in any circuit, rather than the amount which is done in a given time. It is evident that this rate can always be found by dividing the amount of work by the number of seconds taken for its performance, but the same result can be arrived at by multiplying together the potential difference and the rate of transference or flow of electricity, instead of the quantity actually transferred in a given time. Now the rate of flow of electricity is what we know as the current strength, which is measured in amperes. Therefore, if the difference of potential in volts between any two points is multiplied by the resulting current in amperes, the product gives the rate at which energy is being expended, or the rate of working between those two points. The unit rate of working or the unit of *power* is called the *watt*—that is to say, 1 ampere $\times$ 1 volt $=$ 1 watt. Therefore, if a difference of potential of 20 volts between the ends of a wire maintains a current of 3 amperes, the rate of working is $3 \times 20 = 60$ watts.

It is desirable that the relation between mechanical and electrical rates of working should be understood. The mechanical unit is termed the 'horse-power,' and is equal to that rate of working which, if continued for one minute, would expend 33,000 foot-pounds of energy, or raise 33,000 pounds one foot in height. One horse-power is equal to 746 watts, so that, having calculated the number of watts absorbed in any particular case, on dividing this number by 746 we get the rate of working, or rate of expenditure of energy, expressed in horse-power. This power of 746 watts is, therefore, frequently referred to as the electrical horse-power, but since the general introduction of electric lighting another unit of electrical power has been adopted. It is equal to 1,000 watts, or the power expended by 1,000 amperes at a potential difference of 1 volt. A convenient name for this unit is the *kilowatt*, but in practice it is frequently contracted into 'unit.' Thus a dynamo electric machine capable of developing, say, 300 amperes at a potential difference of 200 volts, or $300 \times 200 = 60,000$ watts, is generally referred to as a 60 unit, instead of a 60 kilowatt, machine.

Another very useful practical unit is that generally known as the Board of Trade unit, or the kilowatt-hour. It is, therefore, a unit of energy, and is equal to 1,000-ampere-volt-hours. Thus if a current of 5 amperes at a potential difference of 100 volts be maintained for two hours, one kilowatt-hour will have been expended. The amount of energy expended can therefore be easily calculated in Board of Trade units by multiplying together the current in amperes (C), the electro-motive force in volts (E), and the time in hours (T), and dividing the product by 1,000. Thus

$$\frac{C \times E \times T}{1000} = \text{B. of T. units.}$$

The units described in this chapter are those which are, and which will continue to be, employed in practice by the electric-lighting engineer. No effort should therefore be spared to master the simple relation existing between the ampere, volt, ohm, horse-power, kilowatt, &c.

But it is advisable to know the method by which the various electrical units have been evolved, for they have not been selected arbitrarily, like the pound, yard, and gallon, but are built up on the fundamental conceptions of length, time, and quantity of matter, and are inseparably linked together. Perhaps the simplest measurable quantity which we can conceive is that of length, and in deciding upon a unit of length an effort was made to select some unalterable natural distance. The length of an earth quadrant—that is, the distance from the equator to the pole along a meridian—was agreed upon, and one ten-millionth part of this taken as the practical standard of length, and called a metre. The original measurement of the earth quadrant proved to be considerably in error, and consequently the simple relation between it and the metre was upset. But the metre thus determined is retained as the standard of length, and one hundredth part of this length, called one centimetre, is taken as the basis of the units upon which the system now to be briefly described has been reared. A square centimetre is the area contained in a square each of whose sides is one centimetre, and a cubic centimetre is the volume contained in a cube each of whose edges is one centimetre in length.

The next unit required is that of mass, or quantity of matter,

and it should be remembered that the force of gravity acts upon every body in exact proportion to its mass, or the quantity of matter in it, independently of its size; therefore, what we know as the weight of any substance is exactly proportional to its mass. The unit of mass is called the gramme. It is equal to the mass contained in a cubic centimetre of pure water at its maximum density, i.e. at a temperature of 4° Centigrade.

The third unit, that of time, is called the second. It is the length of time known in England by that name, and is the 86,400th part of a mean solar day.

The great value of a system built upon such units as those described is that it is always possible to recover any one of them, and so reconstruct or verify the system if necessary, although the process is no doubt difficult and tedious. The term 'absolute' has been applied to such a system, but it is not easy to see the precise application of the word here. It is usual, and certainly far better, to refer to it as the centimetre-gramme-second, or briefly the C.G.S., system.

The next conception in order of simplicity is that of the rate at which a mass of matter changes its relative position, or the velocity with which it moves. Velocity is estimated by dividing the distance in centimetres through which a body moves by the time in seconds taken to travel that distance. The unit is a velocity of one centimetre per second.

A mass of matter cannot, by any property belonging to it, change its position or its state of rest or motion, by itself. That which is competent to move, stop, or vary the motion of a mass of matter is called force, and the greater the force, and the longer the time during which it acts, the greater will be the increase or decrease in the velocity of a given mass. The unit of force is called the *dyne*: one dyne is that force which, by acting upon a mass of one gramme during one second, can impart to it a velocity of one centimetre per second.

When the position of a body is changed in opposition to any resisting force, work is done or energy expended, the amount being estimated by multiplying together the force overcome and the distance through which it is overcome. The unit of work is called the *erg*, and it is that work done when a force of one dyne is

overcome through a distance of one centimetre ; the energy expended is in every case equal to the work done, therefore the erg is also the unit of energy. We have seen that the *practical* unit of work, or expenditure of energy, is the joule ; and one joule is equal to ten million ergs. Consequently, the practical unit of power, or rate of doing work, called the watt, is equivalent to ten million ergs per second.

Current strength is measured by the quantity of electricity which flows past any point in a circuit per second. The C.G.S. unit is that current strength which, when one centimetre of its path—that is to say, one centimetre of the conductor carrying the current—is curved into an arc of one centimetre radius, exerts a force of one dyne upon a unit magnet pole placed at its centre. The conditions of this unit will, however, be better understood after studying Chapter IV. The practical unit which is called the 'ampere' is equal to one-tenth of this C.G.S. unit.

The C.G.S. unit quantity of electricity is that quantity conveyed by unit current in unit time. The practical unit, the coulomb, is therefore also one-tenth of the C.G.S. unit.

The unit difference of potential between two points exists when one erg of work has to be performed in urging one unit of electricity against that potential difference, or when one erg is expended by the flow of one unit of electricity from one point to the other. The volt or practical unit is 100,000,000 times the absolute unit.

Unit resistance exists when unit difference of potential causes a current of unit strength to flow through it. It follows, therefore, that the ohm is equal to 1,000,000,000 absolute units.

The units which chiefly claim our attention are those of current, quantity, potential difference, and resistance. It is not possible to provide an invariable physical standard of either of these except resistance, which fact to a certain extent increases the importance attached to the unit of resistance. As has been pointed out, a reliable physical standard, in the form of a column of mercury of certain dimensions, has been selected to represent the ohm.

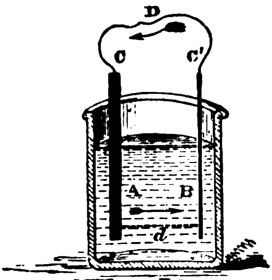
CHAPTER III.

PRIMARY BATTERIES

A CURRENT of electricity can be maintained in a number of ways. One of these is by means of primary cells. A primary cell consists of a vessel containing a saline or acidulated solution, in which are immersed two solid conducting bodies, one of which is more assailable than the other by the liquid. When two or more cells are joined together to increase the effect, the combination is known as a battery.

Primary cells can be divided into two classes, viz. (*a*) single-fluid, or those in which only one solution is used, and (*b*) double-fluid, or those in which two solutions are employed.

FIG. 15.



The single-fluid cells are typified by the 'simple cell,' which was referred to on page 2, and which consists of a glass or earthenware vessel (fig. 15) nearly filled with water acidulated with a small proportion of, say, sulphuric acid, and containing a piece of zinc, A, and a piece of copper, B. On connecting the plates by a piece of wire, C′ C, and thereby allowing the current to flow, the surface of the zinc is attacked and sulphate of zinc is formed, hydrogen gas being liberated at the surface of the plate B.

This reaction may be represented by an equation, thus :—

$$\underset{\text{Zinc.}}{Zn} + \underset{\text{Sulphuric acid.}}{SO_4H_2} = \underset{\text{Sulphate of zinc.}}{SO_4Zn} + \underset{\text{Hydrogen.}}{H_2}$$

No chemical effect whatever is produced on the surface of the plate B, and it may here be noticed that the plate which is more

or less dissolved is called the positive plate, the other being called the negative plate. Chemical action may be supposed to take place throughout the entire length of the liquid or the distance between the plates, but it is not manifest except at the surfaces of the plates, and it is usually considered to commence at the positive plate—that is to say, the acid particles, or, more correctly speaking, molecules, in contact with the zinc plate may be assumed to be the first decomposed, the hydrogen thus liberated attacking the next succeeding acid molecules in a similar manner. Hydrogen is again liberated, which again in its turn decomposes the adjacent acid molecules. A series of decompositions and recompositions is thus propagated throughout the entire liquid by a process of repetition, molecule for molecule, resulting finally in the deposition of the free hydrogen on the copper or negative plate. As the hydrogen thus deposited does not enter directly into chemical union with any of the simple metals, it remains in the gaseous state. The resultant changes present the appearance of the acid alone being affected, while the water remains constant and unchanged. The action may be expressed in chemical formulæ, thus :—

Before action

$$\underset{\text{Zinc or }+}{\Big|}\ \overline{SO_4H_2}\ \overline{SO_4H_2}\ \overline{SO_4H_2}\ \overline{SO_4H_2}\ \overline{SO_4H_2}\ \underset{\text{Copper or }-}{\Big|}$$

In action

$$\underset{\text{Zinc or }+}{\Big|}\ SO_4\ \overline{H_2SO_4}\ \overline{H_2SO_4}\ \overline{H_2SO_4}\ \overline{H_2SO_4}\ H_2\ \underset{\text{Copper or }-}{\Big|}$$

The hydrogen is here released in a definite ratio to the amount of zinc dissolved. In fact, we may take it as an established law that the ratio between the weight of zinc dissolved and that of the hydrogen, &c., released by the passage of the current, is invariable, and that this ratio is dependent upon the respective 'electro-chemical equivalents.'

We see by the above equation that for every atom or equivalent of zinc dissolved or converted into sulphate of zinc, two atoms of hydrogen are liberated. An atom may be defined as the smallest possible quantity of any substance capable of entering into or passing out of combination ; and it will be seen, on referring to the accompanying table of atomic weights, or of the

relative weights of individual atoms of some of the more important substances, that an atom of hydrogen weighs less than one of any other substance :—

TABLE OF ATOMIC WEIGHTS AND EQUIVALENTS

Elements	Symbol and Valency	Atomic Weight	Chemical Equivalent	Electro-chemical Equivalent (Milligrammes per Coulomb)
ELECTRO-POSITIVE				
Hydrogen	H^1	1·	1·	·010384
Potassium	K^1	39·04	39·04	·40539
Sodium	Na^1	22·99	22·99	·23873
Aluminium	Al^3	27·3	9·1	·09449
Magnesium	Mg^2	23·94	11·97	·12430
Gold	Au^3	196·2	65·4	·67911
Silver	Ag^1	107·66	107·66	1·11800
Copper (Cupric) . .	Cu^2	63·	31·5	·32709
,, (Cuprous) .	Cu^1	63·	63·	·65419
Mercury (Mercuric) .	Hg^2	199·8	99·9	1·03740
,, (Mercurous) .	Hg^1	199·8	199·8	2·07470
Tin (Stannic) . .	Sn^4	117·8	29·45	·30581
,, (Stannous) .	Sn^2	117·8	58·9	·61162
Iron (Ferric) . .	Fe^3	55·9	18·64	·19356
,, (Ferrous) . .	Fe^2	55·9	27·95	·29035
Nickel . . .	Ni^2	58·6	29·3	·30425
Zinc	Zn^2	65·	32·5	·33696
Lead	Pb^2	206·4	103·2	1·07160
ELECTRO-NEGATIVE				
Oxygen	O^2	15·96	7·98	·08286
Chlorine	Cl^1	35·37	35·37	·36728
Iodine	I^1	126·53	126·53	1·31390
Bromine	Br^1	79·75	79·75	·82812
Nitrogen	N^3	14·01	4·67	·04849

It is in consequence of this fact that hydrogen is taken as the standard in calculating the atomic weights of the various simple or elementary bodies. It will also be observed that an atom of zinc weighs sixty-five times as much as an atom of hydrogen. The meaning of the equation, therefore, is that for every sixty-five parts by weight of zinc dissolved, two parts by weight of hydrogen are liberated ; consequently, if we again regard the relative deposition of hydrogen as the standard, the weight of zinc dissolved will be 32·5 times as much, or, in other words, the electro-chemical equivalent of hydrogen being unity, that of zinc is 32·5. The equivalents of the other elementary bodies enumerated in the

table have been calculated in a similar way. The 'electro-chemical equivalents' are obtained by multiplying together the weight of the hydrogen liberated by one coulomb and the chemical equivalent of each of the other elementary bodies.

The liberated hydrogen, in consequence of its low specific gravity, exhibits a tendency to rise through the water and escape into the air. Only a portion, however, of the gas escapes in this way, a large proportion adhering to the copper plate and forming, as it were, a gaseous film over the metallic surface. This accumulation, due to a variety of causes, is facilitated by the opposite electrical conditions of the copper and hydrogen which cause a mutual attraction to set in. There is a double effect of the accumulation which soon becomes apparent, for a gradual diminution in the current sets in, consequent first on the decrease in the copper surface exposed to the liquid (which involves a proportional increase in the internal resistance of the cell), and. secondly, on the tendency on the part of the positively electrified hydrogen film to set up a contrary current. Free hydrogen is, in fact, more oxidisable and therefore more positive than the zinc itself. When this condition is arrived at, the cell is said to be polarised—that is to say, the two surfaces, zinc and hydrogen, are brought to nearly the same potential, and as a consequence the current strength is correspondingly reduced. The effect of the passage of a current being, therefore, a reduction of the effective electro-motive force of the cell, such a combination is manifestly useless for purposes requiring a continuous and uniform current—that is to say, a current of 'constant' strength.

To overcome this really strong objection Smee constructed a cell, the peculiarity of which consisted in the nature of the surface of the negative plate. It had been ascertained that a smooth surface engenders a much more rapid accumulation of hydrogen than does a roughened surface. Accordingly, he used for his negative plate a thin sheet of silver covered with platinum in a state of very fine division, so that an irregular surface was produced. So treated the plate is known as platinised silver. There are two zinc plates connected to the same terminal, but placed one on each side of the silver, the solution being 1 of acid to 10 of water. This cell, which is still largely used, is considerably more

lasting than the simple cell; the unevenness of the negative surface facilitates the ascension of the hydrogen particles more nearly in proportion to the rate of production. It has also a higher electro-motive force because of the substitution for copper of a more electro-negative plate. This form of battery is useful where currents are required for brief periods, but it is far from being a constant cell, that is, one which yields a *continuous and uniform* current. When, however, the cell is made of abnormally large proportions, it approximates more nearly to the condition of a constant cell, and is used as such by many electro-platers.

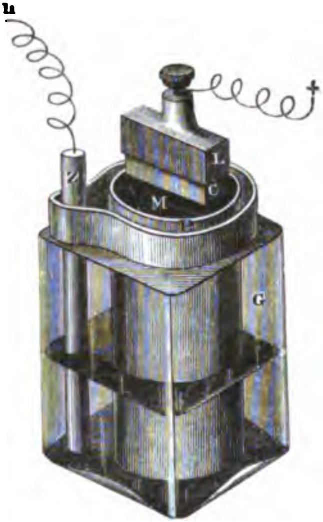
The Smee cell is capable of being manufactured in a very compact form. The silver foil is fixed in a frame made by fastening together four pieces of wood about half an inch square in section, the upper edge of the foil being connected to a brass terminal on the top of the frame. The plates of zinc, a trifle larger than the foil, are placed against the two sides of the frame and the whole are then clamped together by a strong brass terminal or clamp which is placed in contact with the zincs. The advantage gained by this form of construction is that the internal resistance of the cell is very low; first, because the two zinc plates are opposite to the two sides of the foil, and, secondly, because the distance between the foil and the zincs is very small. The wooden frame is necessary, to support the thin silver foil and to prevent it touching either of the zinc plates.

A simple and useful modification of the Smee cell consists of a plate of zinc and a plate of platinised carbon, the upper portion of the latter being rendered non-porous by immersion in hot paraffin wax. The solution is one of dilute sulphuric acid, the acid being, however, very pure. The hydrogen bubbles can be seen rising freely through the solution, instead of adhering to the uneven surface of the negative plate. The resistance of the cell is very low, and its electro-motive force, after a few minutes, remains steady at about half a volt.

A far more important cell is the Leclanché (fig. 16), in which a zinc rod, *z*, is used as the positive plate, while the negative plate C takes the form of a rod or slab of gas carbon, or of prepared carbon. The gas carbon is one of the by-products in the manufacture of gas, and is formed by the condensation of a portion of

the carbon in the cooler portions of the retort. The prepared carbon is made by subjecting to considerable pressure, at a high temperature, a mixture of powdered carbon and some treacly substance which is employed for cementing the carbon particles. The carbon plate is placed inside a vessel of porous (unglazed) earthenware, which is then filled with a mixture of crushed, but not powdered, carbon and black oxide of manganese. The latter should be granular, of about the size of peas, care being taken to exclude powder or dust. The outer vessel, G, is generally of glass, which enables the condition of the cell to be observed without removing any of the parts. The liquid consists of a saturated solution of sal-ammoniac, or chloride of ammonium, the porosity of the inner jar allowing the solution to diffuse itself somewhat freely, and so to moisten the mixture of carbon and black oxide.

FIG. 16.



The zinc combines with the chlorine of the sal-ammoniac, forming zinc chloride, simultaneously releasing hydrogen and ammonia, which latter dissolves in the water until a saturated solution is obtained—that is to say, until the solution holds as much as it can support—after which it escapes as a gas readily recognised by its characteristic odour. It may, however, be remarked that water is not saturated with ammonia until it has absorbed 727 times its volume of the gas at a temperature of 15·5° C. or 60° F. The hydrogen, so far, remains free, as shown by the equation :—

$$\underset{\text{Zinc.}}{Zn} + \underset{\text{Sal-ammoniac.}}{2NH_4Cl} = \underset{\text{Zinc chloride.}}{ZnCl_2} + \underset{\text{Ammonia.}}{2NH_3} + \underset{\text{Hydrogen.}}{H_2}$$

It is, however, ultimately released inside the inner vessel, and

there it deprives the manganic oxide of some of its oxygen, forming water and sesqui-oxide of manganese, thus :—

$$\underset{\text{Hydrogen.}}{H_2} + \underset{\text{Manganic oxide.}}{2MnO_2} = \underset{\text{Water.}}{OH_2} + \underset{\text{Sesqui-oxide of manganese.}}{Mn_2O_3}$$

The entire action may be represented by a single equation, thus :—

$$Zn + 2NH_4Cl + 2MnO_2 = ZnCl_2 + 2NH_3 + OH_2 + Mn_2O_3.$$

The action so represented is, of course, similar to that of the simple cell, in so far as concerns the propagation of the series of decompositions and recompositions. There is, however, a subsequent or secondary reaction between the zinc chloride and the other constituents of the solution, resulting in the formation of what are called double salts, which tend to impede the efficient working of the cell.

One great advantage this battery has over most, if not all other forms, is that it does not in any way deteriorate by inactivity, unless the evaporation of the water can be regarded in this light, but even that may be prevented. It is no unusual experience for Leclanché cells to remain in work for upwards of a year without the necessity for any attention whatever, and even then it is probable that a little water is all that is required. It will be seen, from a study of the equations given above, that the working of the battery results in the gradual absorption of the zinc, and the decomposition of the sal-ammoniac, &c., which accordingly require replenishing at times. A whitish-yellow turbidity in the solution indicates the presence of an excessive amount of zinc chloride in proportion to the amount of sal-ammoniac, which latter should then be increased, although it would be as well to remove a portion of the solution and then fill up with water before adding the sal-ammoniac.

Considerable care is taken in the construction of this cell. As both sal-ammoniac and ammonia are corrosive and attack copper, brass, &c., all the exposed metallic surfaces should be well served with gutta-percha, pitch, paraffin wax, or some other non-corrodible and impervious material.

Where the batteries are made in very large quantities, it is the

practice to drill two small holes through the upper extremities of the carbons, and, after raising these ends to a high temperature, to dip them into melted paraffin wax. They are subsequently placed into a mould containing molten lead, a terminal or binding-screw being cast into this leaden cap at the same time. The function of the wax is to close the pores in the upper portion of the carbon, and so to prevent the ammoniacal solution from creeping up to the terminal or leaden cap. Lead is interposed between the waxed carbon and the brass terminal because it is the least assailable of the ordinary metals. Pitch is run over the carbon-manganese mixture to keep the mixture and the carbon rod in position, holes being made in it, however, to permit any hydrogen or other gases that may be formed to escape, or any air that might be in the pot to be expelled when it is placed in the solution. The upper parts of the porous pot, and the zinc rod and the connections, are likewise coated with pitch. Sometimes an india-rubber cover is made to fit over the top of the battery, so as to hold the porous pot and the zinc permanently in position, and to prevent the evaporation of the water.

The electro-motive force of this battery is nearly twice that of the simple cell, while, owing to the large surface exposed, more particularly at the negative plate, the internal resistance is also low. The chief objection to this battery is the great rapidity with which it polarises and so becomes temporarily useless, owing probably to the fact that hydrogen is liberated faster than the manganic oxide can be decomposed. Consequently, a more or less perfect film of hydrogen is deposited over the surface of the carbon. That this is the case is in a measure demonstrated by the fact that if the cell is allowed to stand idle for a brief interval of time it will again yield its full current. This intermittent action obviously limits very materially the cell's sphere of usefulness. The defect, although very marked when the resistance of the circuit is very low, is reduced to a minimum when the resistance is high, because the current is then feeble and the chemical reactions proportionately less. The fact that the constituents of the cell remain inactive when the cell is idle, is a point of very considerable importance, and is a very useful feature, for it means that there is no wasteful action in the battery, such as

we shall find there is in practically every other type of battery—at least, in every battery in which an acid plays a part. Cleanliness is, however, absolutely necessary in dealing with the Leclanché, or, indeed, with any other form of battery, and it is essential that the containing vessel, whether of glass or earthenware, should be kept dry externally. The latter desideratum is usually accomplished by coating the upper portion of the outer surface of the vessel with pitch or some other such substance as will not permit the liquid to 'creep' over its surface, for the salt (sal-ammoniac) has a strong tendency to crystallise out. Should the solution be allowed to creep, we have to contend not only with the waste of salt so occasioned, but also with the 'leakage' of electricity that would take place over the moistened external surface.

There is a modification of the Leclanché which is of some importance and which is known as the 'agglomerate' Leclanché. The negative element consists of a carbon plate or block, having in contact with it blocks of agglomerated carbon and manganese. The latter are prepared by intimately mixing 40 parts of manganic oxide, 55 parts of gas carbon, and 5 parts of gum lac resin, and submitting the mixture, placed in a steel mould, to a temperature of 100° C., applying at the same time considerable hydraulic pressure. The result is a solid compact mass, and, as the chief function of the porous pot in the older type is to support the mixture of crushed carbon and manganic oxide, it is apparent that that vessel, which materially increases the internal resistance of the cell, can be dispensed with. India-rubber bands placed round the agglomerated blocks (which in their turn embrace the carbon block), keep the whole of the compound negative element together. In the earlier forms of agglomerate cell, rectangular blocks of agglomerated manganic oxide and carbon were held against the two faces of a flat plate or block of carbon, and the india-rubber bands holding the three blocks together were specially made so as to hold also the zinc rod, which was of the usual type.

But a much better form is that known as the 6-block agglomerate (fig. 17), which is very extensively used. The negative element consists of a block of carbon with six fluted sides, which is capped with lead and fitted with a terminal after the top of it has been steeped in hot paraffin wax. In each of the sides

is laid a round stick of the agglomerated carbon and manganic oxide, the whole being wrapped round with a piece of coarse canvas, and held in position by a couple of stout india-rubber bands. The canvas does not, of course, prevent intimate contact between the rods and the solution, nor does it appreciably increase the internal resistance of the cell, its function being simply to prevent pieces of the agglomerate rods falling out, and 'short-circuiting' the cell, by joining the positive and negative elements together. Instead of employing a zinc rod for the positive element, a large piece of sheet zinc (about $\frac{1}{8}$ inch thick) is rolled into a cylinder, the approaching edges being, however, kept a quarter of an inch or so apart to allow of the free circulation of the solution. In consequence of the very large increase in the amount of the surfaces thus exposed to the liquid, the internal resistance is very considerably reduced, polarisation being also to a great extent prevented or at least impeded. The current produced is therefore much more uniform than that from the old type Leclanché.

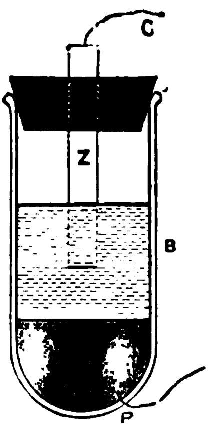
FIG. 17.

The electro-motive force of any one of the many forms of Leclanché cell may be taken as being approximately 1·5 volt, while the internal resistance may range from ·25$^\omega$ to 3$^\omega$ or 4$^\omega$, according to the size of the elements and the construction of the cell.

The 'Standard' cell (fig. 18), invented by Mr. Latimer Clark, is an important one. It is designed solely as a standard of electro-motive force, and is largely employed for purposes of measurement. It may be made in a small glass vessel, such as a short wide test-tube, a layer of pure distilled mercury, M, being employed as the negative plate, which covers the bottom of the

glass vessel to a depth of half an inch or so. Over this is placed the 'liquid' or electrolyte, which consists of a thick paste, B, made by mixing mercurous sulphate with a saturated solution of zinc sulphate. The positive element is a rod of pure distilled zinc, Z, which dips into the paste. It is usual to seal the battery by means of marine glue or india-rubber, S. Connection is made with the zinc by means of a copper wire, C, soldered to the upper end of the zinc rod which passes through the glue or rubber stopper. A platinum wire, P, fused into the bottom of the vessel, makes contact with the mercury.

FIG. 18.



It is highly essential that the constituents of the cell should be absolutely pure, hence the necessity for re-distilling the zinc and mercury. The mercurous sulphate can be made by dissolving pure mercury, placed in excess, in hot pure sulphuric acid. The sulphate is an insoluble white powder, and should be well washed with distilled water before it is mixed with the zinc sulphate, to remove any trace of the mercuric sulphate or of free acid. The mercuric contains a smaller proportion of mercury than the mercurous sulphate, and, on the addition of water, imparts to it a yellowish tinge.

The chemical action which takes place during the passage of a current is to decompose the mercurous sulphate, adding the mercury released to that already in the vessel, an equivalent of zinc being simultaneously dissolved off the positive rod, thus increasing the amount of sulphate of zinc in the paste.

The electro-motive force of this cell is 1·435 volt, or, in terms of the B.A. unit, 1·454 volt, and is exceedingly uniform, providing only that it is never allowed to send a current of any appreciable strength. If the resistance of the circuit is low, the current becomes proportionally strong, and the mercury salt is not then capable of being decomposed at a corresponding rate, whence polarisation sets in and the electro-motive force falls in consequence. Under the most favourable conditions, a cell which has in this way been lowered in its electro-motive force takes a con-

siderable time to recover, and frequently the injury is permanent —that is to say, the cell becomes practically useless. The electromotive force also decreases with an increase of temperature, the rate being about 0·08 per cent. per degree Centigrade.

The commercial form of Clark cell constructed after the plan of Dr. Muirhead is illustrated in fig. 19. Instead of using a layer of mercury, the platinum electrode A, fused through the glass-containing vessel, is made of a long piece of wire which is coiled into a close flat spiral and coated with mercury, either by heating and then immersing it in a mercury bath, or by heating the mercury and the platinum together. The spiral is then embedded in the paste, composed of pure mercurous sulphate and a saturated solution of pure zinc sulphate, *p*. The pure zinc rod, *z*, is dipped into the paste, and a cement stopper, *c*, holds the whole firmly together, so that the cell is made more portable than that shown in fig. 18, which has the disadvantage that the constituents of the cell are liable to become mixed if it is not used very carefully. The mercury deposited on the platinum spiral is sufficient to form or maintain the negative element or 'plate,' so that a layer of mercury is not really necessary.

FIG. 19.

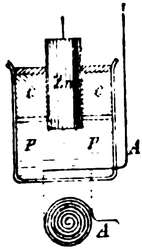


FIG. 20.

Fig. 20 shows the method employed for casing in. A cylindrical brass case with an ebonite cover is used, and contains two cells which can be balanced one against the other to test their relative electro-motive force, or they can be used together and give a double electro-motive force. A thermometer is likewise provided, the bulb being inside and the tube bent so as to lie over the scale on the cover. This is an important, though simple

innovation, and assists in the avoidance of an error due to a varying temperature. To avoid any error due to polarisation it is better to employ the cell only for the purpose of making an effort to send a current, and noting the maximum potential difference it can produce, which will be equal to the electro-motive force of the cell. For example, it may be used to charge a standard condenser, or in conjunction with the 'potentiometer' described in Chapter VI.

The only other form of single-fluid battery which we shall notice is that in which a solution of bichromate of potash is employed, and which is frequently made in the form shown in the diagram (fig. 21). It consists of an alternation of zinc and carbon plates (always one more of carbon than of zinc), placed in a glass vessel containing the solution. The carbons are all connected together so as to give a large negative surface, as also are the zincs, so as to present a large positive surface to the solution. In most cases the zincs are attached to a metal rod, *a*, which slides in a hole in the cover, so that by raising the rod the plates can be readily removed from the liquid and the wasteful consumption of the zinc and bichromate of potash which would otherwise take place when the cell is idle prevented.

FIG. 21.

The solution consists of 1 part by weight of bichromate of potash, 2 parts of good sulphuric acid (of 1·8 specific gravity), and 12 parts of clean water. The bichromate of potash is first pulverised and then added slowly to the acid, stirring all the time. This converts the bichromate of potash into chromic anhydride and potassic sulphate, which precipitates in a beautiful crystalline formation, the chemical reactions being indicated by the equation :—

$$\underset{\text{Bichromate of potash.}}{K_2Cr_2O_7} + \underset{\text{Sulphuric acid.}}{7SO_4H_2} = \underset{\text{Chromic anhydride.}}{2CrO_3} + \underset{\text{Potassic sulphate.}}{K_2SO_4} + \underset{\text{Water.}}{OH_2} + \underset{\text{Sulphuric acid.}}{6SO_4H_2}$$

Water is then added slowly, when the crystals are dissolved and the chromic anhydride converted into chromic hydrate or

acid (H_2CrO_4) by the absorption of water, a quantity of the water being taken up, with the usual result that follows the admixture of sulphuric acid and water—viz. the evolution of a considerable amount of heat. The energy with which the acid unites with the water is very great, and it is this that necessitates the slow addition of the latter. If poured on too abruptly there is considerable danger of the mixture being ejected from the vessel and scattered about the person or on anything that may be near. As the acid is exceedingly corrosive, it is impossible to take too much precaution when adding the water. In ordinary cases where the acid and water are to be mixed it is by far the safer plan to add the acid to the water, as the former will then find plenty of the latter to satisfy its almost insatiable thirst.

When the solution of the crystals is completed and when the liquid has cooled down to the ordinary temperature, it is ready for use. On completing the circuit and allowing the current to flow, the zinc is dissolved, forming zinc sulphate, and the chromic acid is converted into chromic sulphate, water being liberated. The reaction may be expressed by the equation :—

$$\underset{\text{Zinc.}}{3Zn} + \underset{\text{Sulphuric acid.}}{6H_2SO_4} + \underset{\text{Chromic acid.}}{2H_2CrO_4} = \underset{\text{Zinc sulphate.}}{3ZnSO_4} + \underset{\text{Water.}}{8OH_2} + \underset{\text{Chromic sulphate.}}{Cr_23(SO_4)}$$

This battery has an electro-motive force of about 2 volts, while its resistance is very low. It yields, therefore, a considerable current, which does not, however, last long, rarely more than an hour or so, because of the rapidity with which the cell becomes polarised. On the other hand, when only used occasionally, the same solution will last for a very long time. As there is a tendency, by secondary chemical reactions taking place between the various constituents of the cell, to form hard crystals of a double salt (known as chrome alum) which at times cause a fracture of the jar, it is advisable to avoid square or flat cells for this battery. As we shall presently see, a modification is extensively used on account of its high electro-motive force, its low internal resistance, and its approximation to constancy.

We come now to consider the double-liquid batteries, the great aim of which is to obtain constancy, even if at the cost of a higher internal resistance. The chief obstacle to constancy, we

have seen, is the accumulation of hydrogen on the negative surface, which hydrogen must therefore be absorbed. Daniell, in 1836, was the first to achieve this object, which he did by using a metallic salt in the neighbourhood of the negative plate, separated from the zinc and acid solution by means of a porous division which, on being moistened, allowed the current to pass through it, but which at the same time prevented, or rather impeded, the intermingling of the two solutions. The conception of a porous division was certainly a brilliant idea, but so also was that which determined the kind of solution which was to surround the negative plate. This liquid contains a large quantity of the very same metal as that of which the plate itself is constructed, and it is due in a great measure to this fact that the Daniell cell stands alone, and pre-eminently so, as *the* constant cell. The cell is put together in a great variety of shapes and patterns, varying with the purpose to which it is intended to be applied. It consists essentially of an outer porcelain or other non-porous vessel, containing the zinc. Inside this is placed an unglazed earthenware vessel, which contains a piece of thin sheet copper. The porous vessel is nearly filled with copper sulphate (known more generally as bluestone), and water is poured on till the level is about the same as that in the outer vessel, which contains a solution of one part of sulphuric acid, or of zinc sulphate, with 12 to 20 parts of water.

The chemical reactions which take place in the Daniell cell are of a very simple character. On completing the circuit the zinc enters into action with the sulphuric acid and forms sulphate of zinc ($ZnSO_4$), releasing free hydrogen (H_2), in precisely the same way as in the simple cell. This hydrogen is not, however, liberated on the surface of the negative or copper plate, but at or near the porous partition where the two liquids meet. The hydrogen coming into the presence of the copper sulphate solution, proceeds at once to displace the metal from its combination, setting it free as metallic copper, and taking its place to form a new equivalent of sulphuric acid. The liberated copper acts in a manner very much akin to that of the free hydrogen in the acid solution that is, it breaks up the next molecule of copper sulphate, and produces a new molecule of the same compound by

replacement, and so on until the surface of the negative plate is ultimately reached, on which is deposited the finally released copper particle.

A little reflection will reveal to the student something of the greatness of the advance thus made by Daniell. In the first place, we find the released hydrogen, which was the great drawback in the simple cell, taken up entirely by a very easily decomposable salt, and thus prevented from polarising the battery. Furthermore, instead of the deposition of the foreign hydrogen film on the copper plate, copper purer than can be obtained by any other simple process is deposited. In fact, a similar process is employed commercially for the extraction of copper from its ores, and for the refinement of comparatively impure bars. The action that takes place from the zinc to the copper surface may be expressed thus :—

$$\underset{\text{Zinc.}}{Zn} + \underset{\substack{\text{Sulphuric}\\ \text{acid.}}}{SO_4H_2} + \underset{\substack{\text{Copper}\\ \text{sulphate.}}}{SO_4Cu} = \underset{\substack{\text{Zinc}\\ \text{sulphate.}}}{ZnSo_4} + \underset{\substack{\text{Sulphuric}\\ \text{acid.}}}{SO_4H_2} + \underset{\text{Copper.}}{Cu}$$

Or showing the effect on a few of the intermediate molecules :—

Before action.

$$\underset{\text{Zinc.}}{|}\ SO_4H_2\ \ SO_4H_2\ \ SO_4H_2\ \underset{\substack{\text{Porous}\\ \text{partition.}}}{|}\ SO_4Cu\ \ SO_4Cu\ \ SO_4Cu\ \underset{\text{Copper.}}{|}$$

In action.

$$\underset{\text{Zinc.}}{|}\ SO_4\ \ H_2SO_4\ \ H_2SO_4\ \ H_2\ \underset{\substack{\text{Porous}\\ \text{partition.}}}{|}\ SO_4\ \ CuSO_4\ \ CuSO_4\ \ Cu\ \underset{\text{Copper.}}{|}$$

We see here that for every atom of zinc dissolved one atom of copper is deposited, and for every molecule of sulphuric acid decomposed by the zinc, or for every molecule of cupric sulphate decomposed by the nascent hydrogen, one molecule of sulphuric acid is formed. Theoretically, then, the gross quantity of free sulphuric acid should remain constant, zinc sulphate should be continuously increasing, while the sulphate of copper should diminish in precisely the same ratio—that is, one molecule or equivalent of zinc sulphate should be formed for every molecule or equivalent of cupric sulphate that is decomposed. Further, for every 65 parts by weight of zinc dissolved, 63 parts by weight of copper should be deposited.

A weak solution of zinc sulphate is frequently substituted for the sulphuric acid solution. In that case no hydrogen at all is generated, so that polarisation from this cause is altogether impossible. The series of chemical reactions presents the same general features. On joining up, the zinc sulphate attacks the metallic zinc, fresh particles or molecules of the salt are formed, and metallic zinc liberated in place of the hydrogen which is produced when sulphuric acid is employed. The liberated zinc decomposes the copper sulphate, forming more zinc sulphate and liberating the copper. Eventually, copper is deposited on the copper plate, the reactions being set forth in the equation :—

$$\underset{\text{Zinc.}}{Zn} + \underset{\text{Zinc sulphate.}}{SO_4Zn} + \underset{\text{Copper sulphate.}}{SO_4Cu} = \underset{\text{Zinc sulphate.}}{2ZnSO_4} + \underset{\text{Copper.}}{Cu}$$

The substitution of the zinc sulphate for the acid has also the effect of reducing the wasteful consumption of the zinc. Unless the cell is required for immediate use there is really no need to add even the zinc sulphate to the water, the reason for which will be seen presently.

The chemical changes, however, which are brought about in the Daniell by the propagation of the current, constitute only a portion, and that a by no means large one, of the total amount of chemical change that ensues on fitting up the cell. The porosity of the unglazed earthenware partition, while it allows the two solutions to come into contact, also permits of their diffusion or gradual mixing. All liquids do not diffuse at a uniform rate, the rate of diffusion varying inversely as the square of their specific gravities. The immediate consequence of this is, that some of the copper sulphate solution passes through into the zinc division, where its copper is displaced by zinc, thereby converting the copper sulphate into zinc sulphate. The copper so displaced is deposited in a black spongy mass upon the surface of the zinc, or is precipitated to the bottom of the cell as battery 'mud.' All this means so much waste, for the zinc is dissolved and the copper sulphate decomposed, without the production of any available current of electricity. The deposit on the zinc plate converts the cell, in a great measure, into one with two copper surfaces.

When the battery is intended only for occasional use, or when

the external circuit is of relatively high resistance, it is much preferable to use somewhat denser porous partitions, whereby the diffusion of the solutions is to some extent prevented, or at least hindered. The presence of denser porous partitions implies, of course, a proportional increase in the internal resistance of the battery. It may here be mentioned that white unglazed porcelain is harder and less porous than the red variety, and is therefore generally to be preferred. Generally speaking, it is not advisable to employ the Daniell for occasional work on account of the loss due to the interchange of the solutions and the wasteful consumption of the zinc and sulphate of copper.

Great care must also be taken that the various constituents of the cell are of the purest possible character, and all metallic joints must be electrically continuous. A small percentage of impurity in either of the solutions will have most deleterious effects. Three substances are required as pure as our knowledge can render them. The copper sulphate must, above all things, be pure, because of the weakness of the chemical affinity between sulphuric acid and copper. In the event of the salt not being so, the impurities will precipitate the copper and then small 'local actions' will be called into existence, much to the prejudice of the primary or main current. The impurity most common in copper sulphate is iron, which may be readily detected, for, as liquids are essentially diffusive, a small test-tube full will give the same quantitative as well as qualitative result as any larger quantity. Acid solutions of copper are of a brilliant greenish blue hue, while the corresponding ammoniacal solutions, due to the free addition of ammonia solution, are of a beautiful deep blue colour. If, therefore, we add an excess of ammonia to the acid solution (*i.e.* more than sufficient to neutralise the acid), the copper will be readily retained in the solution, but with the change of colour mentioned above. Iron, however, while it is soluble in acid, is precipitated by ammonia—that is to say, the ammonia will not allow the iron to remain in solution. Should there, therefore, be any iron in the acid solution, it will be precipitated as a dark powder on the addition of the alkaline ammonia. The sulphuric acid or sulphate of zinc, when used, must likewise be free from impurities, the chief of which is again iron. This metal in sulphuric acid gives it a

yellowish tinge, even when in small quantities. Good acid should be as colourless as pure water, and when poured from one vessel to another should, if of the requisite strength and specific gravity, have the viscidity of oil. The porous partition, unless carefully made, is liable to contain small particles of cinder, &c., and these tend to decompose the cupric sulphate with a precipitation of the copper, which forms itself into nuggets in the pores of the earthenware and frequently chip or even completely fracture it.

The zinc should be pure, or as nearly so as it can be obtained. Chemically pure zinc, however, is manufactured with great difficulty, and is consequently very expensive. The presence of foreign matter is, nevertheless, a very great deterrent to the good working of the cell, for it must be remembered that the presence in a solution of two metals in contact, or otherwise electrically connected, always results in the production of electrical currents. If, therefore, there are particles of foreign metals mixed up with the zinc, there necessarily occurs local currents which act disadvantageously in at least two ways—first by wasting the zinc, and secondly by weakening the main current. As zinc is positive to every available substance (the only metals positive to it being potassium and sodium, which, on account of their extreme affinity for water, are never employed for battery purposes), the admixture of particles, say, of iron, tin, or arsenic, causes small currents to travel from the zinc to those particles, and while the impurities remain to a great extent unaffected (because of their being the negative element), the zinc is constantly suffering a loss by consumption or conversion into a salt. These minute currents are furthermore produced on the surface of the zinc, and must, as already mentioned, interfere considerably with the production of the primary current. The difficulties arising from the presence of impurities are also increased if the zinc is imperfectly or improperly manufactured. The molecular arrangement (or the relative position of the molecules) must be homogeneous throughout the surfaces of each plate, otherwise currents will be set up between the softer and harder parts of the zinc—in a word, they possess slightly different electrical properties, so that even if chemically pure zinc were procured, it would not follow as a matter of course that we should be secured against this source of wasteful

local action. Concentrated sulphuric acid has, it may be mentioned, no effect on pure zinc provided it is properly annealed—that is to say, that the surfaces have been softened and made molecularly homogeneous. The acid can, therefore, furnish us with a tolerably reliable test for the degree of purity and equable texture possessed by the metal.

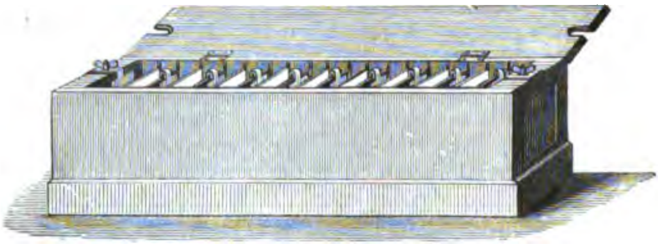
The effect both of the presence of any impurity and of unequal hardness can, however, be effectually overcome, at least for a time, by the process known as 'amalgamation.' This process consists in first thoroughly cleansing the surfaces of the metal by immersing it for a time in a dilute sulphuric or hydrochloric acid solution, and subsequently (but while still wet with the acid) coating the surfaces with mercury. This operation is generally recommended to be performed by rubbing the mercury on with a sponge or piece of cloth at the end of a stick; but this is a very irksome and tedious operation, more especially when the zincs are cylindrical, and it is quite as, if not more, efficacious to pour the mercury (which should afterwards be used for no other purpose) into a flat vessel and lay or roll the zincs in it. This may be thought a wasteful process, but the superabundant mercury can be easily removed by wiping the surfaces over and then standing them on a dish, to allow any mercury that may be still free to fall off. This method is much to be preferred when it is required to amalgamate a large number of plates. A very little mercury deposited at the bottom of the zinc division in the battery will suffice to keep the plate well amalgamated for a long time.

By adopting the process of amalgamation the commonest zinc can be rendered thoroughly serviceable for a greater or less period according to the degree of effectiveness with which the process has been carried out. As to its rationale, it appears evident that the function of the mercury is to homogenise the molecular arrangement by uniformly softening the zinc and forming with it a regular amalgam unassailable by pure sulphuric acid. The amalgam in an almost liquid state glides over and covers up any impure particles that have not been dissolved off by the washing process; as the zinc wears away these particles fall out and drop to the bottom of the cell to do no further harm.

The mercury does not enter into action with the acid or in

any other way interfere with the efficient working of the cell, but on joining up the battery the acid attacks and dissolves the zinc more or less uniformly, the mercury eating its way inwards as the superficial zinc particles enter into the solution.

FIG. 22.



The circular form of battery is extravagant in the matter of shelf or floor space, while the square or flat types, which have practically superseded the circular ones, are essentially compact, and are for that reason to be preferred. The square type consists generally of

FIG. 23.

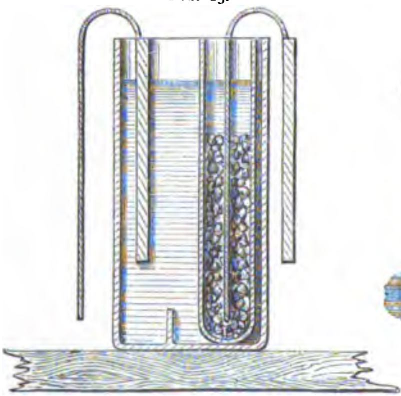
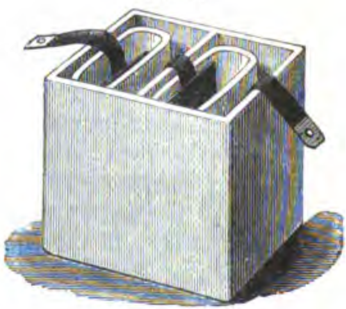


FIG. 24.



a wooden box or trough, into which five double or ten single cells of white glazed porcelain or ebonite are placed, when it presents a neat and compact appearance, as shown in fig. 22. Fig. 23 is a section of one of the single-cell porcelain vessels, fig. 24

illustrating the double-cell form. The latter is square and is very convenient. There is a little ridge along the bottom of each cell (see fig. 23) to keep the flat porous vessel in position. This porous vessel containing the copper plate is filled up with copper sulphate crystals, the zinc, which should be not less than $\frac{1}{4}$ inch thick (to allow for waste by local action), being suspended in the zinc sulphate solution. It will be noticed that the copper plate is attached to the zinc of the next adjacent cell. It is usual in practice to rivet one end of a copper strap on to the copper plate, the zinc being cast on to the other end of the strap. In this way expensive binding screws or terminals are dispensed with, and a good and substantial contact is ensured. The last zinc and the last copper are connected to brass terminals, which become respectively the negative and positive poles of the battery.

Nothing but clean water (hard water should, if possible, be avoided) is poured into the zinc division, but enough is employed to bring it up to within about a quarter of an inch of the top of the zinc plate. The battery at the end of about twenty-four hours will be found to be in working order, the sulphate having dissolved in the copper division and enough passed through the porous partition to start the chemical action. Under these circumstances, then, a portion of the cupric sulphate that would otherwise be wasted is utilised to convert the water into a solution of zinc sulphate. If the cell is wanted for immediate use, the zinc division must be filled with a weak solution of sulphate of zinc (or sulphuric acid), and the copper division with a saturated solution of sulphate of copper; action then commences at once. It is often more convenient to dispense with the trough or box and place the cells side by side on a shelf. The advantage of this in an extensive battery room is apparent.

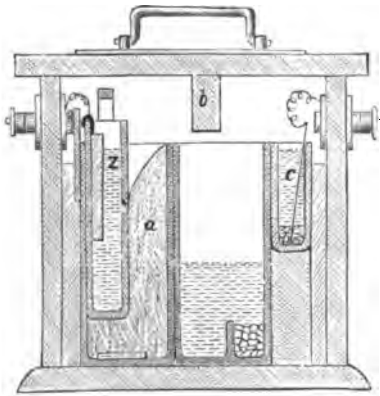
All porous pots should be dipped, top and bottom, in melted paraffin wax, so as by filling up the pores to prevent the solutions mingling too freely or rising to the top above the level of the liquids, and so allowing the water to evaporate and the salts to crystallise out. One side of the flat porous pots may also be paraffined with advantage—viz. the side which is remote from the zinc.

A porous pot which has been once used should not be allowed

to get dry, as the crystals which form on drying will chip it, and soon render it useless.

The Daniell cell, when in good condition, can be employed as a standard of electro-motive force, and owing to the ease with which the copper salt is decomposed, the cell possesses one great advantage over the Clark standard cell, in that it does not polarise when joined on short circuit, even for a considerable time. It has, however, the disadvantage that for accurate measurement it requires a certain amount of attention which must be particularly directed to the zinc division, to keep it free from copper.

FIG. 25

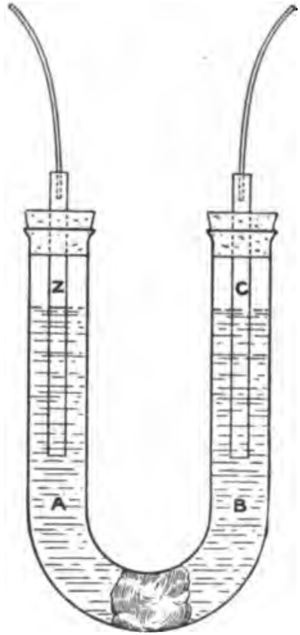


A very handy and convenient form of Standard Daniell is that used in the Postal Telegraph service, and shown in fig. 25. In a square wooden box, provided with two terminals for connection, are three water-tight chambers. When the cell is not in use, the copper plate *c* is removed to the right-hand chamber containing copper sulphate solution, the zinc plate *z* and the porous pot containing it being transferred to the left-hand chamber. This porous pot is supplied with a semi-saturated solution of zinc sulphate, the copper sulphate solution and its reserve of crystals being placed in the middle chamber. All that is then necessary to put the cell in working order is to remove the copper and the porous pot into the centre division. The stud *b* attached to the lid prevents it being shut down unless the porous pot has been removed to the outer chamber. Such a cell will maintain an electro-motive force of 1·07 to 1·079 volt for a considerable time, providing that the copper and porous pot are removed to their respective idle chambers between the tests.

There is another form of Standard Daniell, which we have found very reliable, very easy to make, and very inexpensive. It consists of a U-tube (fig. 26) about half an inch in diameter and

5 inches long in the leg. A little cotton wool is pushed down to the bottom of the bend to form the porous partition. One leg, B, is provided with a quantity of a saturated solution of sulphate of copper, and the other leg, A, with a semi-saturated solution of sulphate of zinc. A piece of pure copper wire, say three-sixteenths of an inch thick, forms the negative plate, the positive plate consisting of a rod of chemically pure zinc, such as can be obtained of any dealer in chemical materials. These rods are fixed in position and the ends of the tube sealed by means of corks or india-rubber stoppers. The cell can be secured to a wooden stand by means of an india-rubber band, and wires connected to the rods can be joined to terminals fitted on the board. Such a cell can be put together in a few minutes, and always secures a reliable standard of electro-motive force, quite good enough for all ordinary practical work, but of course its internal resistance is too high to enable it to be used to give a standard current in the same way that the cell just described is usually employed.

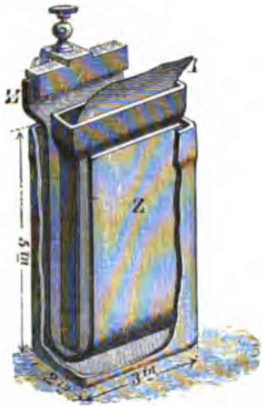
FIG. 26.



We have seen that Daniell absorbed the freed hydrogen by causing it to reduce a metallic salt : Grove and Bunsen in their batteries, to be now described, oxidised the hydrogen by means of an acid, water being produced by this hydrogen instead of sulphuric acid or sulphate of zinc. In the negative division concentrated nitric acid is used, into which Grove dipped platinum foil, while Bunsen adopted gas-carbon. Zinc, as usual, constituted the positive plate in each case, the liquid placed with it being a solution of sulphuric acid. The illustration (fig. 27) shows the construction of the Grove. It is usually contained in a flat

rectangular glass, porcelain, or ebonite vessel, porcelain being perhaps the best. The amalgamated zinc plate, z, is bent into a U-shape, and embraces the flat porous pot which contains the platinum foil, P. By this arrangement each surface of the platinum has opposed to it a surface of zinc, the internal resistance being consequently very low. A strong solution of sulphuric acid (about 1 of acid to 7 or 8 of water) is poured into the outer cell and strong nitric acid having a specific gravity of 1·420 is placed in the inner cell with the platinum. The copper or brass connections or terminals should be lacquered except upon those surfaces which take part in the electrical circuit, to protect them as much as possible from the gases which are evolved during the working of the cell.

FIG. 27.



The action is in the first stage similar to that in the Daniell, but there is some diversity of opinion as to what actually transpires in the platinum division. Zinc sulphate is formed by the action of the sulphuric acid on the zinc, and the hydrogen which is thereby released reduces the nitric acid (HNO_3) to water and nitric peroxide (N_2O_4), which ascends as a gas into the air. This gas is distinguishable from all others by its dense brown appearance and its extremely pungent odour.

The chemical reactions may be represented by the equation—

$$\underset{\text{Zinc.}}{Zn} + \underset{\text{Sulphuric acid.}}{SO_4H_2} + \underset{\text{Nitric acid.}}{2HNO_3} = \underset{\text{Zinc Sulphate.}}{ZnSO_4} + \underset{\text{Water.}}{2OH_2} = \underset{\text{Nitric Peroxide.}}{N_2O_4}.$$

It will be noticed that the nitric acid, which, to give the maximum strength of current, should be concentrated, must be seriously weakened as the current is produced. This results, in the first place, from the fact that every atom of hydrogen set free from the sulphuric acid decomposes a portion of the nitric acid, while in the second place the water which is formed dilutes and so weakens the remaining acid. The acid, which, when first poured in,

should be quite colourless, is first turned brown by the peroxide, which is more or less soluble in the acid, changing subsequently to green, when it is practically useless.

The Bunsen cell, which is illustrated in fig. 28, is most frequently made in the circular form. The outer jar is of glazed earthenware or glass, and contains a solution of sulphuric acid, ordinarily in the proportion of 1 of acid to 7 or 8 of water, as in the Grove. Into this is placed a cleft zinc cylinder, and inside this is the porous cell, containing a rod of carbon, immersed in strong nitric acid. The porosity of the carbon enables it to present to the liquid a very extended surface, as compared with the platinum of the Grove cell.

FIG. 28.

The action in the battery is precisely the same as in the Grove, since the carbon and platinum remain chemically unaffected.

The Daniell and the Grove cells are the representatives of two extensive classes of battery. Daniell's has attained its high standard of popularity on account of its cheapness and its constancy. It is much more constant than either of those we have as yet mentioned. The Grove, on the other hand, is very powerful, but, owing to polarisation, it runs down very rapidly, and is not reliable for more than three to four hours at a time. It is, however, important to remember that if the negative plate and its acid are removed from the cell separately and allowed to stand for a time, the acid can be used again and the cell will give a current practically as good as before. The same acid can be used three or four times before it is so reduced in strength as to materially affect the current, a state which, as already mentioned, is indicated by the greenish hue imparted to the acid. The chief use of the Grove cell in England is for experimental purposes. It has the

advantage that it is very compact and portable. The Bunsen has a slightly higher electro-motive force, and it is somewhat cheaper than the Grove. As, however, it is generally constructed in the cylindrical form, it is less convenient.

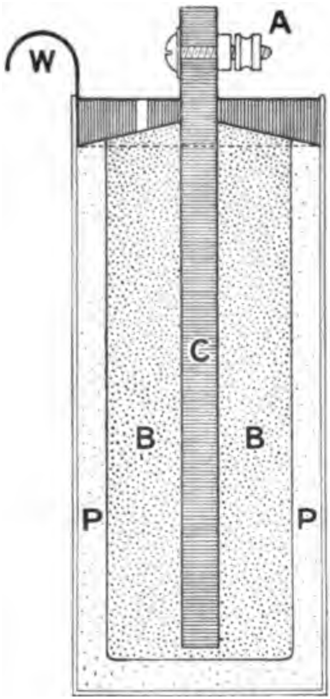
There are many forms of double-fluid bichromate batteries. In nearly all of them zinc and carbon are employed for the positive and negative elements respectively, the difference being, generally speaking, confined to the 'depolarising' solution surrounding the carbon plate. In one of them, however, a great feature is made of the means adopted for keeping the zinc well amalgamated. This cell is known as the 'Fuller,' and it is usually made up in a round earthenware jar, in which is placed a comparatively small porous pot containing a zinc rod of peculiar shape, as shown in fig. 29. The zinc is cast on to a stout copper wire which passes almost to the bottom of the rod and helps to keep it intact. Two or three ounces of mercury are placed in the porous pot, which, on the addition of the solution (dilute sulphuric acid), creeps up the surface of the zinc by the force of capillary attraction and so keeps it uniformly and automatically amalgamated. A comparatively small carbon plate is placed in the outer vessel in a solution of bichromate of potash, derived, however, from a stiff paste, of which a quantity is placed in the bottom of the cell, and which contains, probably, a quantity of free chromic acid, soda nitrate, &c. An unusually large quantity of this solution is generally provided in order to maintain its strength for a longer period of time than would be the case were the more usual proportions adopted. The chemical action is practically the same as that in the single-fluid bichromate cell. What is true of the nitric acid cells of Bunsen and Grove is also true, although, perhaps, to a less degree, of each and every form of bichromate of potash or of chromic acid cell—viz. that polarisation and the accompanying reduction in the electro-motive force, and therefore also in the current strength, sets in after the

FIG. 29.

battery has been in use for a few hours more or less. The electro-motive force of the cell is, however, high, averaging 2 volts, and its internal resistance is also very low, whence it finds considerable favour.

A distinct type of cell, known as the 'dry' cell, has during the last few years been brought into somewhat extensive use, but nearly all the forms of this type of cell are in principle modifications of the Leclanché cell, having zinc and carbon for the positive and negative plates, sal-ammoniac to attack the zinc plate, and manganese peroxide to intercept the hydrogen. The electro-motive force is therefore in all cases about the same as that of the Leclanché, viz. 1·5 volt. The chief feature in these cells is the absence of any *liquid*, the materials being made up into a damp paste. It should be manifest that were the cell really dry, chemical action could not take place, and no current could be produced. As it is, the cells are liable to become useless as the moisture in the paste evaporates. One of the best of the many forms of dry cell is that known as the E.C.C. cell, of which a section is given in fig. 30. It is contained in a zinc cylinder, which is at the same time the positive plate, and which is provided with a lining, P, composed of plaster of Paris, flour, chloride of zinc, sal-ammoniac, and water mixed up into a paste, which quickly sets after having been placed in position. Inside this is another paste, B, surrounding the carbon plate, C, and composed of carbon, peroxide of manganese, chloride of zinc, and water. The chloride of zinc, which is increased in

FIG. 30.



amount during the action of the cell, is a deliquescent salt, and it therefore assists in keeping the pastes moist. The top of the cell is sealed in with a layer of pitch or other similar material resting on a layer of silicated cotton. A small hole through the pitch permits the escape of such gases as may be liberated. Connection is made to the carbon by means of a brass terminal screw, A, and to the zinc cylinder by means of a copper wire or strip, W.

When newly made the resistance of the cell is considerably less than half an ohm, but it rises steadily as the contents become dry. The resistance can, however, be lowered again, although not to its initial value, by the introduction through the vent-hole of a little weak solution of sal-ammoniac.

Dry cells of this description are certainly very handy, more particularly for testing operations, where the batteries have to be carried about, as there is no risk of spilling any corrosive solution, and the cells are always immediately available.

Primary batteries are of but little service in electric lighting. They are, of course, valuable for testing purposes, but as sources of current for the electric light they are altogether out of place, except for very small isolated work, owing to the fact that zinc, which is in every case used as the positive plate, and which, being consumed in the generation of the current, corresponds to the coal consumed in an engine, is very many times dearer than coal. Even were expense a question of minor importance, there still remains the fact that primary batteries are very troublesome to maintain, and more often than not give off noxious fumes, which are also as a rule highly corrosive What is really wanted, putting aside altogether the question of expense, is some simple form of cell, of which the constituents can be easily obtained and replaced; from which no injurious fumes can arise; which shall have a high electro-motive force and a low internal resistance, and be fairly constant withal. This is apparently an unobtainable desideratum.

There are three considerations that have to be taken into account when determining what kind and what number of cells it would be most advisable to employ for any particular purpose—first, the relative constancy; secondly, the electro-motive force; and, thirdly, the ratio between the internal resistance of the cell

and the external resistance (or the resistance of the connecting wires and apparatus). It will have been gathered that there is in the matter of electro-motive force and constancy considerable variation. We will not enter here into the matter of expense, for in the end that which is the best cell for any particular purpose generally proves to be also the cheapest. The internal resistance is, however, an important factor. If it were negligible, it would, for example, be possible to maintain a current of one ampere by one Daniell cell having an electromotive force of, say, one volt working through an external resistance of one ohm, for as

$$C = \frac{E}{R}, \text{ then } \frac{1 \text{ volt}}{1 \text{ ohm}} = 1 \text{ ampere.}$$

But the average Daniell cell offers four ohms resistance, so that the current, where R is the external resistance of one ohm, and r the internal resistance, would be

$$\frac{E}{R + r} = \frac{1}{1 + 4} = \cdot 2 \text{ ampere};$$

and if we were to attempt to increase this current materially by the addition of, say, nine other similar cells, we should fail, for then

$$\frac{10E}{R + 10r} = \frac{10}{1 + 40} = \cdot 25 \text{ ampere nearly.}$$

Similarly, with 100 such cells through this unit resistance—

$$\frac{100E}{R + 100r} = \frac{100}{1 + 400} = \cdot 25 \text{ ampere nearly.}$$

We see, then, that increasing the number of cells in this way, when the external resistance is low, produces no correspondingly good effect, for the simple reason that, although we proportionally increase the electro-motive force by so doing, we at the same rate increase the circuit resistance. As a matter of fact, no Daniell cell or battery, unless made of abnormal dimensions, can possibly develop a current of one ampere, its internal resistance being too high.

On the other hand, were we to employ Grove cells (which, for simplicity, we will assume to have an electro-motive force of 2 volts per cell), the advantage of increasing the number of cells on a low

resistance circuit soon becomes apparent. For example, with an external resistance of 1 ohm and an internal resistance of ·2 ohm per cell, one cell would give us

$$\frac{E}{R + r} = \frac{2}{1 + \cdot 2} = 1 \cdot 6 \text{ ampere.}$$

Two such cells would produce

$$\frac{2E}{R + 2r} = \frac{4}{1 + \cdot 4} = 2 \cdot 85 \text{ amperes.}$$

And three cells

$$\frac{3E}{R + 3r} = \frac{6}{1 + \cdot 6} = 3 \cdot 8 \text{ amperes nearly.}$$

Similarly, four cells would give 4·4 amperes, and five cells would yield 5·0 amperes. But from ten cells we should only get

$$\frac{10E}{R + 10r} = \frac{20}{1 + 2} = 6 \cdot 6 \text{ amperes.}$$

While with 100 such cells the current would be

$$\frac{100E}{R + 100r} = \frac{200}{1 + 20} = 9 \cdot 5 \text{ amperes,}$$

showing again that as the internal resistance approaches or exceeds the external, the proportional increase of the current is lessened. When, however, the external resistance is relatively high, say 1,000 ohms, the battery resistance becomes proportionally low, and, therefore, to a certain extent, negligible. The current from one Daniell cell would be

$$C = \frac{E}{R + r} = \frac{1}{1000 + 4} = \cdot 000996 \text{ ampere.}$$

With ten cells we should get

$$\frac{10E}{R + 10r} = \frac{10}{1000 + 40} = \cdot 00961 \text{ ampere,}$$

or, practically, a current of tenfold strength.

Similarly, with a battery of 100 cells, we should get

$$\frac{100E}{R + 100r} = \frac{100}{1000 + 400} = \cdot 0714 \text{ ampere.}$$

Again, one Grove cell would give through 1,000 ohms

$$C = \frac{E}{R + r} = \frac{2}{1000 + \cdot 2} = \cdot 002 \text{ ampere,}$$

and ten cells would give

$$\frac{10E}{R + 10r} = \frac{20}{1000 + 2} = \cdot 0199 \text{ ampere.}$$

From 100 cells we should get—

$$\frac{100E}{R + 100r} = \frac{200}{1000 + 20} = \cdot 196 \text{ ampere.}$$

With either the Daniell or the Grove the strength of the current increases in almost the same ratio as the number of cells when the external resistance is high. But as the Grove is vastly inferior to the Daniell in constancy, and as it is a very expensive form of battery, the deduction is that Daniell cells should be used for circuits of high resistance, compensating for their lower electro-motive force by a corresponding increase in numbers. On the other hand, the Grove, in consequence of its low internal resistance, is better adapted for circuits of low resistance, such as are frequently met with in experimental work.

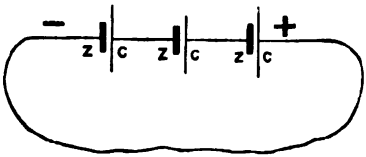
The internal resistance, however, of different cells of any particular type varies inversely as the size of the plates (counting only the active or opposed surfaces). It also varies directly as the distance between them (making due allowance for the resistance of the porous pot, which would, of course, have a constant value unless varied in size or thickness). The meaning of this is plain, for if we were to double the size of the plates we should halve the resistance and proportionally increase the current strength.

The same object is attained by joining cells in 'parallel.' So far we have only considered them as joined in series, that is to say, the copper of one cell joined to the zinc of the next and so on. Under such circumstances the electro-motive force of the battery is equal to the sum of the electro-motive forces of the various cells. If the coppers of two cells are joined together, and likewise the zincs, and the two junction wires connected to the external circuit, a current will be developed by an electro-motive force equal to that of one cell, the joint resistance of the two equal

cells being half that of one of them used separately. The arrangement is, in fact, equivalent to doubling the size of the plates.

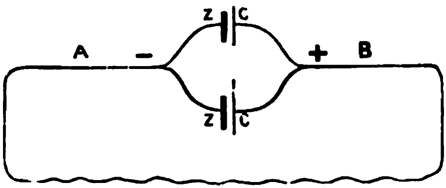
This will, perhaps, be made clearer by a reference to the diagrams, figs. 31, 32, and 33. Fig. 31 represents a battery of

FIG. 31.



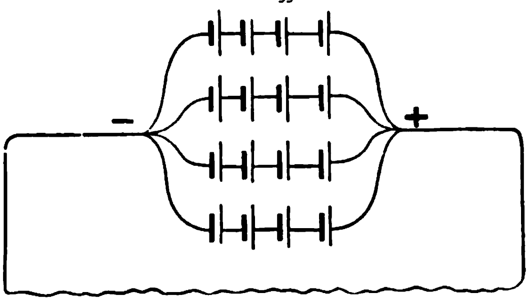
three cells joined in series, the short thick strokes representing the zinc or positive plates, and the long thin ones the copper or nega-

FIG. 32.



tive plates. Fig. 32 shows two cells joined up in parallel. If they are both of exactly the same electro-motive force, no current can

FIG. 33.



flow from C to C or from *z* to *z*, but on joining the external wires A and B together, a current would be generated by each cell and pass through the external circuit from B to A. As already stated, the joint resistance of these two cells would be half that of one of

them, and with a low external resistance the current strength would be increased proportionally. In fig. 33 are shown sixteen cells divided into four sets of four cells each, the sets being joined up in parallel. On completing the external circuit a current will flow, due to an electro-motive force equal to that of four cells, but the battery resistance will be only one-fourth of that of four cells.

The joint resistance of any number of parallel batteries is equal to $\frac{rs}{B}$, where r is the resistance per cell, s the number of such cells joined up in series in each individual battery, and B the number of such batteries joined together in parallel. This is simply an application of the law that with a number of conductors, N, of uniform resistance, R, joined together in parallel, their joint resistance is equal to $\frac{R}{N}$. For rs is the total resistance of each of the batteries joined together in parallel. This arrangement is sometimes very advantageous; for example, if sixteen Daniell cells, each of 1 volt electro-motive force and 4 ohms internal resistance, are employed in series for a circuit of 4 ohms external resistance, the current will be

$$\frac{16}{4 + 64} = \cdot 235 \text{ ampere} \quad . \quad . \quad (1).$$

By dividing the cells into two sets of eight cells each and joining these in parallel, the current is increased, thus

$$\frac{8}{4 + 16} = \cdot 400 \text{ ampere} \quad . \quad . \quad (2).$$

On rearranging the cells, as shown in fig. 33, the current becomes

$$\frac{4}{4 + 4} = \cdot 500 \text{ ampere} \quad . \quad . \quad (3).$$

Pursuing this plan any further, however, results in a diminution of the current, because the gain in reduced resistance is overbalanced by the loss in electromotive force; for example, if eight sets of two cells each are joined in parallel, we get

$$\frac{2}{4 + 1} = \cdot 400 \text{ ampere} \quad . \quad . \quad (4).$$

While with the whole of the sixteen cells joined in parallel we get only

$$\frac{1}{4 + \cdot 25} = \cdot 235 \text{ ampere} \quad . \quad . \quad (5).$$

With circuits of comparatively low external resistance there is, therefore, a best possible arrangement of the cells to give the strongest possible current, and with any given number of cells this arrangement is arrived at when the internal resistance is equal to the external resistance R, or when $R = \frac{rs}{B}$.

Such an arrangement is not, however, economical ; nor, indeed, is any arrangement, unless the external resistance is considerably in excess of the internal. As has been already stated, the strength of the current is the same in all parts of the circuit, consequently in (1) sixteen times as much zinc, &c., is consumed in the sixteen cells as would be consumed in a single cell capable of maintaining an equal current. In (3), however, each set of four cells must be considered as a separate or branch circuit, and only one-fourth of the current flowing in the external circuit would flow through each of these separate sets. The external current is approximately twice as strong as in (1). Therefore the individual current in each cell and the consequent consumption of zinc is only half as great. In (5), where there are sixteen cells in parallel, a current is produced equal to that resulting from a battery of sixteen cells in series, but, the cells being joined up in parallel, only one-sixteenth of this current flows through each cell, so that the total consumption of zinc in the sixteen cells is equal to that in but a single cell in (1), clearly demonstrating the advantage, from an economical point of view, of using batteries much lower in resistance than the wire or apparatus through which the current has to flow.

One important feature concerning the proportion between the electro-motive force of the battery and the difference of potential it can maintain in any given external circuit requires careful consideration, for it is a feature that is frequently lost sight of. It was pointed out in Chapter II. that in any given circuit the fall of potential varies directly as the resistance, so that in (1), where the internal bears to the external resistance the proportion

of 16 to 1, only one-seventeenth of the 16 volts developed by the battery is available in the external circuit, the remaining sixteen-seventeenths being absorbed in overcoming the resistance of the battery. In (3) the resistances outside the battery being equal to that inside, the electro-motive force of 4 volts developed is halved, 2 volts being available for the external circuit. Similarly in (5) the available electro-motive force for the external circuit is sixteen-seventeenths of a volt (the gross electro-motive force developed being 1 volt), or equal to that produced by the sixteen cells joined up in series, as in (1), where, as already shown, the consumption of materials is sixteen times as great; and, speaking generally, we may say that

$$P = E \frac{R}{R + r}.$$

Where E is the electro-motive force developed by the battery, R is the external resistance, r is the internal resistance, and P the available potential difference at the terminals of the battery. For example, with a battery, as in (4), whose internal resistance is 1 ohm working through an external resistance of 4 ohms, and having an electro-motive force of 2 volts, the available potential difference will be

$$P = 2 \frac{4}{4 + 1} = 1 \cdot 6 \text{ volt}.$$

The available potential difference can also be ascertained in another way which does not involve the necessity for ascertaining the external resistance. Ohm's law declares $C = \frac{E}{R}$ or, $E = CR$. And this is true either of a complete circuit or simply of a part of a circuit. If, for instance, in a circuit of known or of unknown total resistance the current strength is found to be, say, 1·5 ampere, and that a portion of the circuit offers a resistance of 3 ohms, then the fall of potential, or the electro-motive force absorbed, in that portion of the circuit will be

$$E = CR = 1 \cdot 5 \times 3 = 4 \cdot 5 \text{ volts}.$$

If the known resistance is that of the battery (r), it follows that 4·5 volts will be the electro-motive force absorbed by the battery, and

if that is deducted from the total electro-motive force developed (say, 20 volts), the remainder will be the available potential difference for the external circuit, or

$$P = E - Cr = 20 - (1{\cdot}5 \times 3) = 15{\cdot}5 \text{ volts.}$$

Occasion sometimes arises for substituting one form of battery for another without making any appreciable change in the current strength. If the internal resistance were negligible, this would, of course, be a matter of no difficulty; but even when it is requisite to make allowance for the battery resistance, a simple formula can be employed to ascertain the number of cells necessary to develop a given current strength. For example, suppose that a battery of 100 cells, with an electro-motive force of 1 volt and an internal resistance of 4 ohms per cell, sends a current through an external resistance of 400 ohms, then the current will be

$$\frac{100E}{100r + R} = \frac{100}{400 + 400} = {\cdot}125 \text{ ampere.}$$

Substituting some other form of battery with an electro-motive force of 2 volts and an internal resistance of 1 ohm, and letting n be the number of such cells necessary to develop $0{\cdot}125$ ampere, then

$$\frac{n \times 2}{n \times 1 + 400} = {\cdot}125 = \frac{1}{8} \text{ ampere,}$$

that is to say,

$$\frac{2n}{n + 400} = \frac{1}{8},$$

or,

$$16n = n + 400$$

$$15n = 400$$

$$n = \frac{400}{15} = 26{\cdot}\dot{6}$$

Twenty-seven of these 2-volt cells would maintain in the circuit a current of

$$\frac{27E}{27r + 400} = \frac{54}{27 + 400} = {\cdot}126 \text{ ampere.}$$

Twenty-six cells would be insufficient for the purpose. This formula also possesses the advantage of providing the same poten-

difference at the terminals of the battery, as well as that of ishing the number of cells necessary to develop an equally ıg current.

The student should make every effort to master these simple ılations and the principles involved, and he will then be in a :ion to readily understand almost any similar problem which present itself in connection with dynamo machines and the plex circuits upon which they are usually employed.

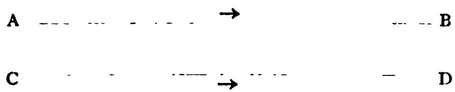
CHAPTER IV.

MEASUREMENT OF CURRENT STRENGTH

HAVING in the preceding chapters shown how a current of electricity can be generated and maintained, and having also explained the various units by which we can measure that current, as well as the resistance, and the pressure or electro-motive force which maintains the current, it behoves us now to turn our attention to the methods of making such measurements, and to the consideration of the laws involved. In order to make the student's progress at this difficult stage as easy as possible, we will approach the subject experimentally.

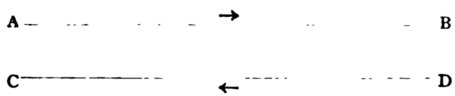
If a wire, A B (fig. 34), carrying a current is brought near another wire, C D, also carrying a current, it is found that there is

FIG. 34.



a decided action between the two wires. If the currents are flowing in the same direction, as shown by the arrow-heads in fig. 34, the wires are attracted one to the other. On the other hand, if the currents travel in opposite directions, as in fig. 35, repulsion ensues.

FIG. 35.

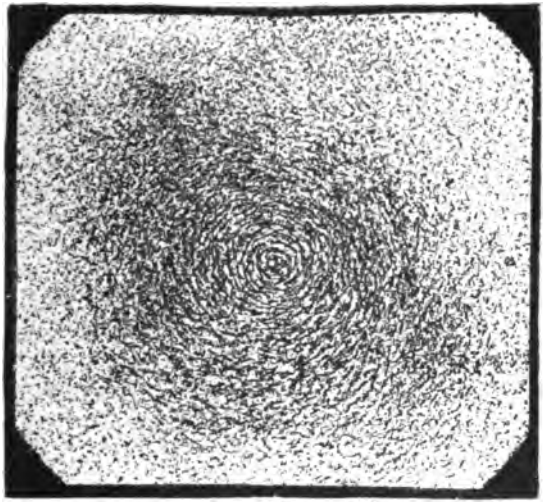


The force of this attraction or repulsion depends, among other considerations, upon the strength of the current. It would be

possible, therefore, to take advantage of this effect as affording a means of estimating or measuring current strength, and a device for so doing will be described presently.

Now it is impossible for any action to take place between the two wires without the aid of some intervening medium to transmit the force. This medium is the same as that which transmits the electrical stresses in the other or static state of electricity, that state in which a body affected by it is said to be electrified or

FIG. 36.



charged with electricity, and is, in all probability, the light-carrying ether.

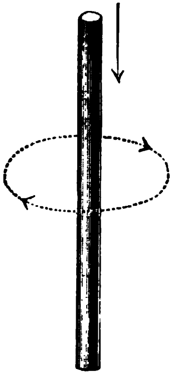
Although it is difficult to understand the precise action in this case, it is easy to show experimentally the direction in which the force acts.

If we thread a wire through a piece of cardboard, send a strong current through the wire, and then sprinkle iron filings on the cardboard, they will arrange themselves in concentric circles round the wire as shown in fig. 36. This arrangement is caused solely by the current and may be observed at any part of the wire. The

lines thus marked out, which show the direction in which the force due to the current acts upon the filings, are called 'lines of force.'

As in the case of the imaginary lines considered in Chapter I., it is necessary to assume for these lines also a certain direction. That direction along a line of force, indicated by the arrows in fig. 37, is called the 'positive' direction. The direction can be impressed upon the memory by thinking of the act of using a corkscrew. If the longitudinal direction of the screw, either *into* or *out* of the cork, be taken to represent the direction of the current, then the positive direction of the lines of force will be that in which the handle rotates, so that if in fig. 37 the downward direction of the current were reversed, the positive direction of the lines of force would be in the opposite direction to that indicated by the arrow-heads. The space around the wire in which the effect of the current is perceptible is called an 'electro-magnetic field,' and it is important to remember that the strength of this field is exactly proportional to the strength of the current producing it. It extends from the axis of the wire as a centre throughout the surrounding space, but as the distance from the wire increases, the effect is weakened until it at last becomes so feeble as to be imperceptible. The lines of force traversing this field obey precisely the same laws as those laid down for the lines due to a static charge, and the interaction between two sets of lines of force can always be predicted by remembering that their universal tendency is to coincide in direction and to shorten themselves.

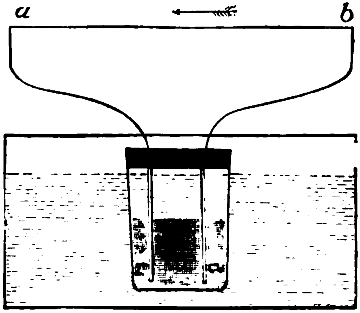
FIG. 37.



Reverting to the experiment with the two wires carrying the currents, it may be said that the force exerted between them always tends to move them so that they shall take up such a position that the currents flow in the same common direction (as in fig. 34) and that the wires as nearly as possible coincide. To prove this, it is necessary to allow at least one of the wires to be capable of moving freely and with as little restraint or friction as possible. This can be done by means of a simple device for constructing a movable or floating battery cell. Let a cork be fitted to a small

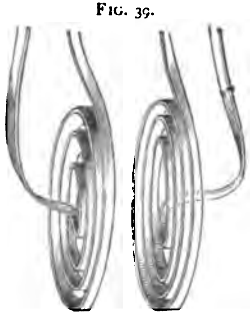
glass beaker partly filled with dilute sulphuric acid, and through the cork pass wires carrying thin strips of zinc and copper or silver, completing the circuit externally by means of a stiff but not too heavy piece of wire, as shown in fig. 38. The small beaker cell can then be placed in a larger beaker, or any other convenient vessel full of water, and, unless too much acid solution has been placed in the smaller beaker or the solid portions are made unnecessarily heavy, the cell will float readily upon the water. If a wire carrying a strong current is placed parallel to the straight part of the wire, *a b*, so that the currents flow in opposite directions, the wire *a b* will be repelled, and, the cell floating away, will turn completely round so that the currents flow in the same direction; it will then be attracted until *a b* lies as near as possible to the other wire.

FIG. 38.



These effects may be increased by increasing the length of the wires, because then a greater number of lines of force are brought into play, but very long straight wires would be cumbersome and, in fact, impracticable. It is, therefore, more convenient to coil them up into flat spirals (fig. 39), covering the wire with silk, cotton, or some insulating material, to prevent adjacent convolutions getting into contact. The effect between the spirals will be similar to that between the same two wires straightened out. For many purposes, however, it is preferable to coil the wire into a long spiral or helix. In fig. 40 one of the helices, A B, is floated in a manner similar to that adopted in fig. 38, the other helix, *a b*, being placed near it. The action between two such helices is very decided, and, being of exactly the same character as that between the straight wires or

FIG. 39.

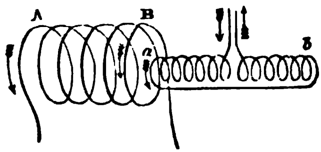


flat spirals, may be predicted by remembering the laws we have just stated.

If the currents are flowing in opposite directions round adjacent ends of the spirals or helices, repulsion will take place, and the floating helix, moving more easily than the other, will recede, and, turning completely round on its vertical axis, will approach with its opposite end to the fixed spiral, as in fig. 40. The currents will then be flowing in the same direction, and the floating helix being comparatively large and its movements not restricted, it will not come to rest until it has threaded itself on to or over the other spiral. Such a spiral or helix of wire acts as if the force resided at its extremities (which are termed 'poles'), and this form of spiral is called a solenoid.

Now the strength of an electro-magnetic field may be measured by the density of its lines of force or the number contained in a

FIG. 40.



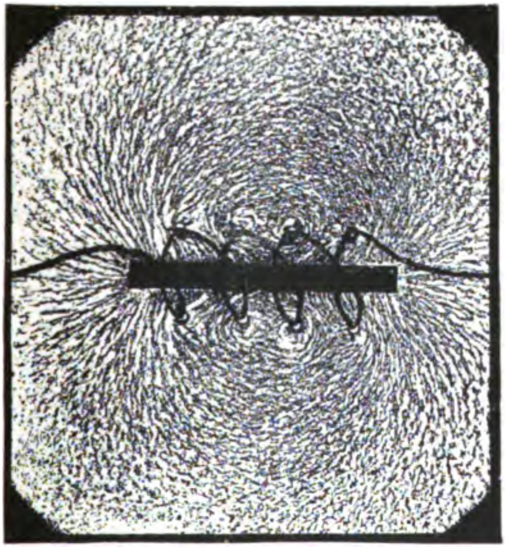
given area. From the experiment shown in fig. 36, it is clear that the lines are much denser near the wire than at a distance from it. This is also the case when the wire is coiled up into a helix. The greater part of them there form little circles, closely embracing the wire from which they are generated, and comparatively few of these circles of force pass through the space at the ends or poles of the solenoid, where, if we consider the action of the helix as a whole, the force, generally speaking, appears to be concentrated. It will be evident that if we can by any means divert the circles of force so as to compel more of them to pass through the ends of the solenoid, then its effective strength will be greatly increased.

Experiment has demonstrated that iron offers a far easier path for these lines of force than the air does—so much easier, in fact, that they will alter their circular shape and extend a considerable distance from their respective portions of the wire in order to pass through a piece of iron. This affords us a ready means of leading

the lines to, and concentrating them at almost any point we please. It may be mentioned that the relative facility with which the lines of force are propagated by good soft iron, or the electromagnetic conductivity of the iron as compared with that of air, may under exceptional circumstances be as high as 2,000 to 1.

If, then, we place a bar of iron inside a solenoid, a large percentage of the lines of force lose their circular form, and, passing through this iron 'core' (as it is called), they leave it at its ends

FIG. 41.



to complete their excursion round the wire from which they were generated. An example of this action of iron is shown in fig. 41,[1] which illustrates the field developed by a powerful current travelling through a solenoid of a few turns, having a core of comparatively small dimensions. Were a larger and more massive core to be introduced, even more of the lines of force would extend

[1] We are indebted to the proprietors of *Engineering* for permission to reproduce figs. 41 to 44.

themselves through the iron instead of circulating in the immediate vicinity of the wire.

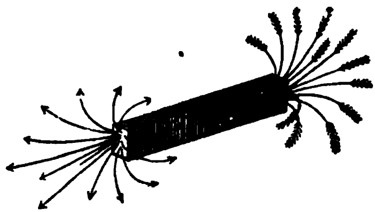
By the introduction of these iron cores the strength of the action between two solenoids is enormously increased, and a still further increase can be obtained by so shaping the iron that the greatest possible facilities are offered for the lines of force set up by the one solenoid to traverse the space occupied by the majority of those due to the other. The designing of the shape and dimensions of an iron core often becomes an extremely important matter, as, for example, in the case of the dynamo electric machines hereafter to be described, in which it is necessary to concentrate an exceedingly powerful field in such a manner that it shall be approximately uniform over a comparatively large space. In such cases the iron cores may be more than a ton in weight, and they are not only expensive to construct, but a considerable expenditure of energy is also required to keep them magnetised. There is, therefore, great scope for effecting economy by making the design such that the cores may be cheaply constructed and yet act efficiently. The student will do well in such cases to always endeavour to think of the iron as simply affording a means of diverting the lines of force set up by the current into just that part of the field where they are required to act. The precise effect on the iron itself is, to a great extent, still a matter for speculation, but it must be remembered that the only way of actually increasing the number of the lines of force setting up the field is by either increasing the current itself, or by increasing the length of the wire and adding to the electro-motive force sufficiently to maintain the same current strength.

The amount of attraction or repulsion exhibited by the solenoids furnished with their iron cores might be used as a means of measuring current strength, but the arrangement is not a convenient one, owing chiefly to the difficulty in obtaining perfect freedom of motion, the liability of variation in the current strength, and the varying properties of the iron.

Were it not for these disadvantages we could keep the electromagnetic force of one of the solenoids constant, and send the currents to be compared and measured through the other. But here Nature comes in to aid us, for it is found that if a piece of

hard iron or steel is used as a core for the solenoid, it retains more or less permanently a large portion of the electro-magnetic properties originally produced by the current. The power or ability of retaining such effects or properties is known as the 'retentivity' of the iron or steel, and depends entirely upon its chemical composition and mechanical or molecular structure. This retentivity is the same property as that hitherto known as 'coercive force,' which was certainly a misnomer. If retentivity corresponds to anything at all, it is to *inertia* rather than to anything that can fairly be described as coercive. The similarity to mechanical inertia is seen in the fact that those samples which transmit the lines of force freely, retain scarcely any of the influences producible by them, while, on the other hand, hard iron and steel, which resist the propagation of the lines of force, resist

FIG. 42.



equally well the vanishing of these lines after the cessation of the current which called them into existence.

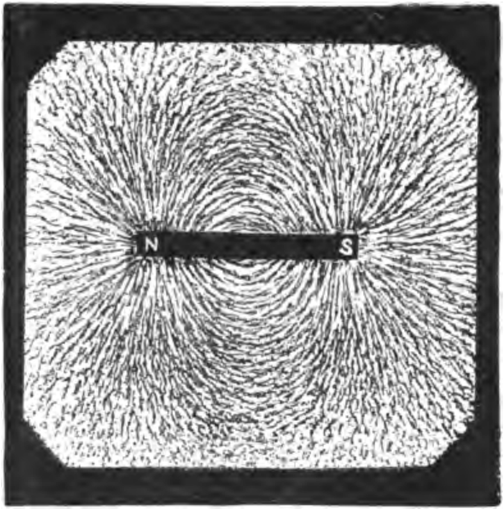
A piece of iron or steel which acquires and so retains the power of acting as a solenoid, is called a permanent magnet, or simply a magnet, and its extremities are also called poles. The lines of force still enter and leave the steel as they did before it was removed from the helix, the direction being shown in fig 42. The end, s, at which they enter is called the south-seeking pole of the magnet, and the other its north-seeking pole.

The actual arrangement imparted to iron filings sprinkled on a sheet of paper placed over a permanent steel magnet is beautifully illustrated in fig. 43. Such a distribution of the filings would take place in any plane parallel to the axis of the magnet, for the lines of force radiate from the poles similarly in all directions. The

distribution observed when the paper is placed on the end of the magnet and at right angles to its axis is shown in fig. 44.

If we know the direction in which the current passes round a piece of iron or steel, it is easy to predict the direction of its polarity; for if we look at the end of the bar, and the current is then flowing round it in a right-handed direction, as in fig. 45, that end will be a south-seeking pole; but if the current flow in a left-handed direction, as in fig. 46, that end will be a north-seeking pole.

FIG. 43.



It is the practice to enter into a detailed description of the difference between right- and left-handed helices with a view to facilitating a recollection of the electro magnetic polarity. Thus a left-handed helix (fig. 47) is one in which, from whichever end the current enters, it will travel in the opposite direction to that taken by the hands of a clock, and will develop north-seeking polarity at the end at which it enters and south-seeking polarity at the end of emergence. Conversely, a right-handed helix (fig. 48) is one in which the current will travel round in the same

direction as the clock-hands. In this, the entering end becomes a south pole and the other a north pole. But all this is super-

FIG. 44.

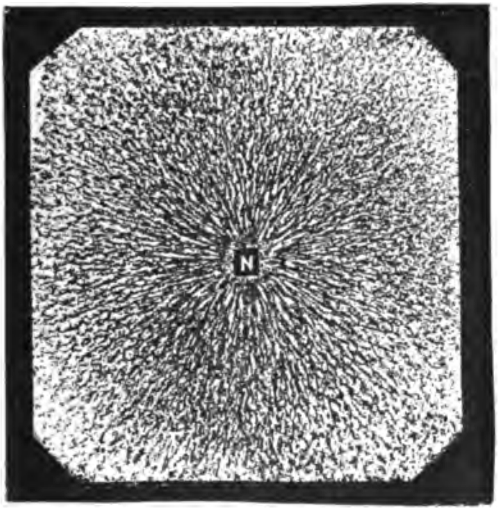


FIG. 45.

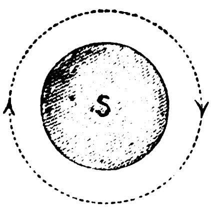


FIG. 46.

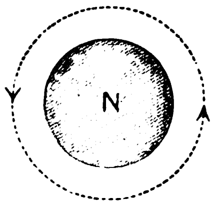


FIG. 47.

fluous. It is sufficient to regard the cause and effect in the way indicated in the preceding paragraph.

It is noteworthy that two magnets act one upon the other in precisely the same manner as two helices or a helix and a magnet, for in every case the movement or motion imparted is such as will tend to make the lines of force coincide. Thus, if one magnet, A (fig. 49), is brought near another, B, which is suspended

FIG. 48.

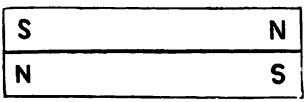
by a thread or pivoted on a needle-point at C, so that it can turn freely about its centre, the force exerted between them will endeavour to make the suspended magnet take up such a position as to allow the lines of force due to both magnets to pass through them in the same direction. This will happen when the magnets

FIG. 49.

are in line and when their opposite poles are adjacent, as shown in fig. 49. In other words, there will be repulsion between similar magnetic poles and attraction between dissimilar ones.

If, however, both magnets are allowed perfect freedom of motion, their ultimate position will be that shown in fig. 50, the

FIG. 50.



magnets then lying side by side with their dissimilar poles adjacent. In this position the coincidence of the lines of force is at a maximum, that is, the lines due to each magnet turn round at the ends and pass through the other, and in so doing assume the easiest path for their completion. If pieces of soft iron, called armatures or keepers, were placed across the extremities of the magnets, the

circuit of the lines of force would be continued through them to such an extent that few or none of the lines would traverse the air. These armatures, are, however, rarely made properly, their mass being far too small, and their shape far from the best possible; but this point we will deal with more fully in Chapter VII.

The strength of a magnet pole can be estimated by measuring the force with which it attracts or repels another pole, the force being equal to the product of the two polar strengths; or, if M represents the strength of one pole, and M_1 the strength of the other, similarly magnetised, the force of their repulsion will be $M \times M_1$. This force of repulsion is not, however, the same at all distances, but varies inversely as the square of the distance, so that we might express the force f, between two magnet poles, by the simple formula,

$$f = \frac{M \times M_1}{d^2},$$

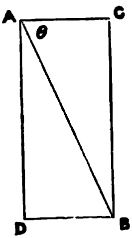
where d equals the distance in centimetres between the poles. Since we cannot possibly obtain a single isolated pole, it is, when endeavouring to verify this statement by experiment, important to bear in mind that the distance between the two poles of each magnet should be as great as possible—or, in other words, that the magnet should be as long as possible—to minimise the error that would be produced by the ever-present tendency of the remote poles to act contrariwise to the adjacent ones.

We have already defined the dyne as the unit of force, and the magnet pole of unit strength is such a one that if placed at a distance of one centimetre from a similar and equal pole, it will repel it with a force of one dyne. Consequently, the strength at any point in any field can be determined by measuring, in dynes, the repulsion at that point of a magnet pole of unit strength. In every case, then, the force acting upon a magnet pole is found by multiplying the strength of the pole by the strength or intensity of the field in which it is placed. In order to numerically compare the strengths of magnetic fields by the relative densities of the lines of force, it is assumed that a field of unit strength contains one line of force per square centimetre.

The earth itself is practically a huge misshapen or irregular magnet, and behaves as such, acting as if its poles were situated

relatively near, but actually at some distance from, the geographical poles. If a magnet needle were suspended so that it could turn freely in a *vertical* plane, it would, with a plane of rotation east and west, point with its north pole vertically downwards; but if the plane of rotation were north and south, the needle would, in London, come to rest with the north-seeking pole dipping downwards, and making an angle—known as the angle of inclination or dip—of about $67\frac{1}{2}°$ with the horizon. If a second magnetic needle were suspended or balanced on a pivot in a *horizontal* plane, it would set itself approximately north and south, the north-seeking pole pointing to the north magnetic pole of the earth. The axis of the magnet—that is, the straight line joining its two poles—would actually make an angle—known as the angle of declination—of about 18°, with the geographical meridian passing through its centre. It will be observed that there is here a case of attraction between the north pole of the earth and the north-seeking pole of the magnet; but this is no contradiction of the law that similar poles repel and dissimilar attract, inasmuch as the magnetic properties of the north pole of the earth are in all respects the same as those of the south-seeking pole of a magnet. The earth's total magnetic force can be resolved into two components at right angles to each other, one acting in a vertical direction, tending to depress the north-seeking pole of the needle, the other acting in a horizontal direction and striving to make it point north and south. Their relative values may be found by the familiar parallelogram of forces (see fig. 51). The line A B is drawn making an angle θ with the horizontal equal to the angle of inclination, and the right-angled parallelogram which has A B for a diagonal completed with its sides horizontal and vertical. Then, if A B represents in length the magnitude of the total magnetic force, A C and A D will be proportional to the horizontal and vertical components respectively.

FIG. 51.

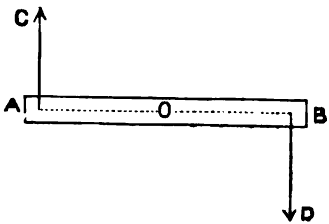


When the magnet is so balanced that it can only move in a horizontal plane, then a large proportion of the force—viz. the vertical component—is simply exerted in pressing the magnet on

its support. The remainder, or the horizontal component only, is effective in making the magnet point towards the magnetic north and south. On the other hand, when the plane of a dipping needle is at right angles to the magnetic meridian, or to the direction of the earth's lines of force, the vertical component only is active, and the magnet points vertically downwards, the horizontal component spending its force in pressing the pivots against their bearings, vainly striving to urge the needle round into the direction of the dip. When the plane of the needle is parallel to the magnetic meridian the total force can then be exerted upon it, the lines of force due to the earth's magnetism then being able to coincide exactly with those of the needle. A horizontally balanced magnetic needle is useful in pointing out the direction of the north and south magnetic poles of the earth.

In consequence of the immensity of the earth as a magnet, its magnetic field is practically uniform over any small space—that is, its lines of force are *parallel* and *equidistant*. It follows, therefore, that the poles of a needle floating on water are attracted or repelled with equal force in any position, and as a consequence of this, the needle does not move bodily towards the north pole of the earth, but is simply directed so as to point north and south. We may here consider the well-known law in mechanics that when two equal forces, parallel but opposite in direction, act at the ends of a rigid bar, they tend to turn it round upon its centre. The turning effect is greatest when the forces act at right angles to the bar, as do C and D in fig. 52, A B being the rigid bar. The amount of this turning effect M is equal to the sum of each of the two forces multiplied by its distance from the centre—that is,

FIG. 52.



$$M = (C \times O\,A) + (D \times O\,B),$$

whence, C being equal to D,

$$M = C\,(O\,A + O\,B)$$

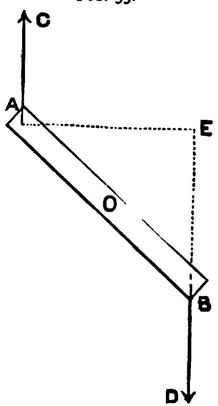
that is, $N = C \times A\,B$,

or the product of one of the equal forces into the perpendicular distance between them.

Such a pair of equal forces is called a couple, the perpendicular distance between their direction being called the arm of the couple; and the turning effect, M, as measured by the product of one of the forces into the arm, is the moment of the couple. As the bar turns round or rotates, the moment M is decreased, the forces being the same but acting at less advantage—in other words, the *leverage* is reduced. This will be more evident from a consideration of fig. 53, where the moment of the couple is C × A E, the new perpendicular between the directions of the forces.

Reverting once more to the experiment with the floating needle, if we call the strength of one of the poles of the needle m, and let H represent the horizontal component of the earth's magnetic field, then the force acting on each end of the needle is $m \times$ H. If we place the needle so as to point east and west, the arm of the couple is equal to the full length l of the needle, whence the moment is $m \times$ H $\times l$. This moment decreases as the needle moves round towards zero, or that position in which it is pointing north and south. The moment is then reduced to nothing, M becoming $m \times$ H $\times$ 0, because the length of the arm is nothing; consequently the needle remains at rest.

FIG. 53.

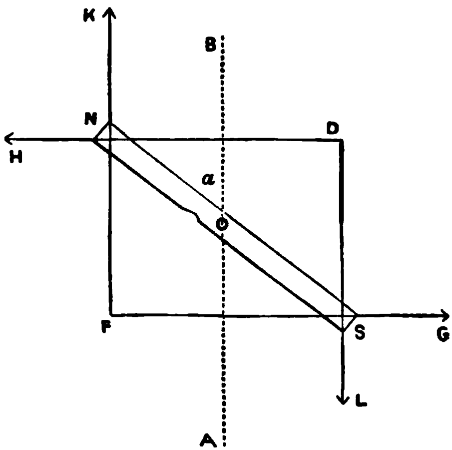


Now, we can cause any current, the strength of which we may desire to measure, to develop a field of strength f at right angles to the earth's directive force—that is to say, we can cause the current to travel north and south, and by so doing deflect a magnetic needle from its zero position. Then the new force acting on each end of the needle will be $m \times f$, where m is again the strength of the magnet pole; and, the length of the arm being calculated as before, the moment will be $m \times f$ multiplied by that arm. Manifestly, the needle will come to rest in a position where the moment of the couple due to the current is equal to that due to the earth.

Let the needle N S (fig. 54) be so deflected by a current, and make an angle., N O B, called the angle of deflection, with the magnetic meridian A B. This angle N O B is, of course, equal to the angle N S D. Let this angle be called $a°$, and let f be the strength of the field due to the current, the direction of the action of which is indicated by the arrows D H and F G. D S is then the perpendicular distance between these directions, whence the moment of the couple due to the current is $m \times f \times$ D S.

By similar reasoning it will be seen that the moment of the couple due to the earth is $m \times$ H $\times$ N D. Now, if the needle has

FIG. 54.



assumed a state of rest, showing that the moments of these two couples are equal, it follows, as a matter of course, that

$$m \times f \times \text{D S} = m \times \text{H} \times \text{N D},$$

and (by cancelling and dividing)

$$f = \text{H}\,\frac{\text{N D}}{\text{D S}}.$$

The ratio $\frac{\text{N D}}{\text{D S}}$ is called the tangent of the angle N S D, which, again, is equal to the angle of deflection $a°$—that is to say,

$$f = \text{H} \tan a°.$$

This strength of field, *f*, is proportional to the current producing it; therefore the current, C_1, is likewise proportional to H tan $a°$.

And this will be true of all currents and all deflections, so that if we let a second current, C_2, cause the needle to be deflected through the angle $b°$, then C_2 must be proportional to H tan $b°$.

Consequently, $C_1 : C_2 :: H \tan a° : H \tan b°$,

that is, $C_1 : C_2 :: \tan a° : \tan b°$,

or the two currents are directly proportional to the tangents of the angles through which they deflect the needle. By referring to a table such as is here given, we can find the numerical value of the

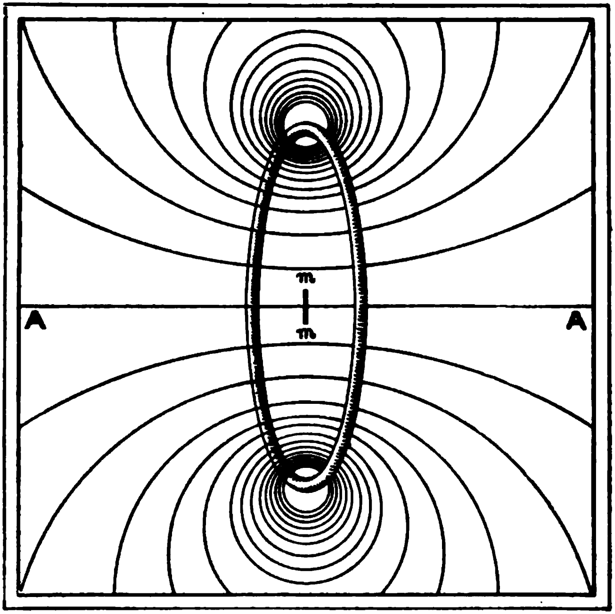
TABLE OF NATURAL SINES AND TANGENTS

Deg.	Sine	Tangent	Deg.	Sine	Tangent	Deg.	Sine	Tangent
1	·017	·017	31	·515	·601	61	·874	1·80
2	·035	·035	32	·530	·625	62	·883	1·88
3	·052	·052	33	·544	·649	63	·891	1·96
4	·070	·070	34	·559	·674	64	·899	2·05
5	·087	·087	35	·573	·700	65	·906	2·14
6	·104	·105	36	·588	·726	66	·913	2·24
7	·122	·123	37	·602	·753	67	·920	2·35
8	·139	·140	38	·615	·781	68	·927	2·47
9	·156	·158	39	·629	·810	69	·933	2·60
10	·173	·176	40	·643	·839	70	·939	2·75
11	·191	·194	41	·656	·869	71	·945	2·90
12	·208	·212	42	·669	·900	72	·951	3·08
13	·225	·231	43	·682	·932	73	·956	3·27
14	·242	·249	44	·694	·965	74	·961	3·49
15	·259	·268	45	·707	1·00	75	·966	3·73
16	·275	·287	46	·719	1·03	76	·970	4·01
17	·292	·306	47	·731	1·07	77	·974	4·33
18	·309	·325	48	·743	1·11	78	·978	4·70
19	·325	·344	49	·755	1·15	79	·901	5·14
20	·342	·364	50	·766	1·19	80	·985	5·67
21	·358	·384	51	·777	1·23	81	·987	6·31
22	·374	·404	52	·788	1·28	82	·990	7·11
23	·391	·424	53	·798	1·33	83	·992	8·14
24	·407	·445	54	·809	1·37	84	·994	9·51
25	·422	·466	55	·819	1·43	85	·966	11·43
26	·438	·488	56	·829	1·48	86	·997	14·30
27	·454	·509	57	·838	1·54	87	·998	19·08
28	·469	·532	58	·848	1·60	88	·999	28·63
29	·485	·554	59	·857	1·66	89	·999	57·29
30	·500	·577	60	·805	1·73	90	1·000	Infinite

tangents of these or other angles, and so can easily compare the strength of the currents.

An instrument which will enable us to make these comparisons is called a tangent galvanometer; but in order to obtain accurate results, one important point must be carefully attended to in designing the instrument, for the foregoing proof only holds good when the two forces forming a pair act parallel to each other in any and every position of the needle. This means, in short, that the field due to the earth, and that due to the current, must be

FIG. 55.



uniform throughout the entire space in which the needle can be moved. Fortunately, we can, by using a very short needle, make this space proportionally small, and thereby render the problem easier. The earth's field, as has been already stated, is uniform, but that due to a current is far from uniform, more particularly in the immediate vicinity of the wire, consequent on the very decided curvature of the lines of force. However, as we get farther away from the wire, these lines approximate more and

more to straight lines, and if we bend the wire carrying the current into a ring of large diameter we shall find a small space at its centre where the lines of force are, to all intents and purposes, straight and parallel. In fig. 55 is shown a horizontal view of the ring and of the distribution of the lines of force in the field. The ellipse represents the ring itself, of which A A is the axis. The magnetic needle is indicated by *m m*. If we suspend the small needle here, the necessary conditions for a tangent galvanometer are satisfied; the needle being too short to permit of its poles being moved into an irregular or variable part of the field.

With a ring 6 inches in diameter we can, in fact, use a needle three-quarters of an inch in length without the risk of introducing any sensible error.

Such a ring of wire, then, with a needle suspended at its centre, will serve to compare and measure current strength according to the law which we have just stated, i.e. each current will be proportional to the tangent of the angle through which it can deflect the needle. When made in a practical form, the tangent galvanometer is one of the most useful pieces of apparatus at our command.

It is important to notice here that a variation in the strength of the magnetic needle will introduce no error in the readings; for if, for instance, a needle partly loses its magnetisation or becomes weak, it is acted upon more feebly by both the earth and the current, and in the same proportion, so that the weakened effect of the earth's field is balanced by the equally weakened effect of the current's field. If the student turns again to the equation on p. 99, he will notice that *m* appears on both sides of the equation, and that it therefore cancels out. It follows that the sensitiveness of a tangent galvanometer is independent of the strength of its magnetic needle. If, therefore, two readings were taken with different needles, but with the same current and with other conditions undisturbed, the deflection would be the same in each case.

Returning to a further consideration of the laws governing the construction of the instrument, it is essential to remember that the force with which a current deflects the needle is proportional

to the length of the wire, and inversely proportional to the square of its distance from the needle. If we increase the size of the coil, we not only increase the distance from the wire to the needle, but also increase the length of the wire in exact proportion to the increase of the radius. Now the former reduces and the latter increases the effect; and this effect may be expressed by saying that the force, f, due to the current's field at the centre of the coil, is proportional to $\frac{2\pi r}{r^2} = \frac{2\pi}{r}$.

The quantity 2π is a constant or invariable quantity; whence it follows that the net result of varying the radius of the coil is that the force with which the needle is deflected varies for the same current inversely as the radius.

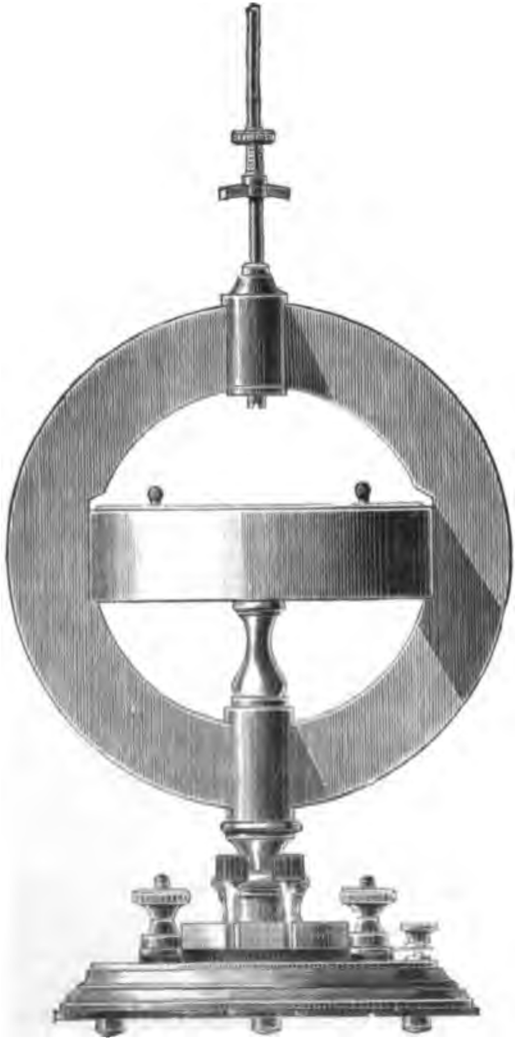
It should also be clear that if we use one coil of 3 inches radius, and another of 6 inches radius, the deflection will be the same when the current in the larger coil is double that in the smaller.

With, however, a single turn of wire 6 inches in diameter, only comparatively strong currents can affect the needle, and, as we have seen, it is not permissible to reduce this diameter for the purpose of obtaining an appreciable deflection with comparatively weak currents. But the difficulty can be easily overcome, for we can increase the length of the wire, without increasing the distance from the needle, by the simple device of coiling it round the needle a number of times. Since the effect on the needle varies directly as the length of the wire, and the length of a wire of two turns is double that of one turn, the effect on the needle is doubled also; in other words, the effect on the needle varies directly as the number of turns of wire in the coil. It follows that, with equal currents, a 6-inch coil of one turn will give the same deflection as a 12-inch coil of two turns.

It must be remembered, however, that if the number of convolutions is increased to any great extent the resistance becomes considerable, and the very act of inserting the galvanometer in a circuit may decrease the current we desire to measure.

Bearing all these points in mind, we will now consider a really practical instrument for the measurement of current strength, selecting for description the pattern which is undoubtedly the best

FIG. 56

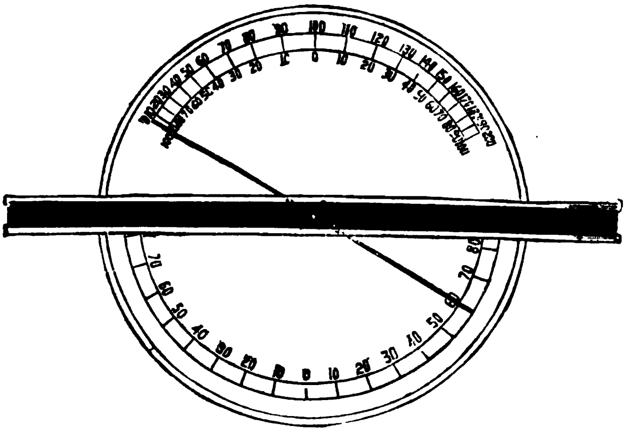


yet constructed—viz. the Post Office tangent galvanometer. A general view of the instrument is shown in fig. 56.

The casing is of brass. The mean diameter of the coil is $6\frac{1}{2}$ inches; the width of the channel in the brass ring which contains the wire is $\frac{5}{16}$ inch, and its depth $\frac{3}{8}$ inch. The length of the needle, which is carefully pivoted with agate on an iridium point, is $\frac{3}{4}$ inch.

As this needle is too short to indicate its own deflections, it carries a light pointer of gilt copper wire, about 5 inches in length,

FIG. 57.



fastened to it at right angles. This pointer moves over an engraved circular scale-plate, one half of which is divided into degrees, the other half into divisions corresponding to the tangents of those degrees, as shown in fig. 57.

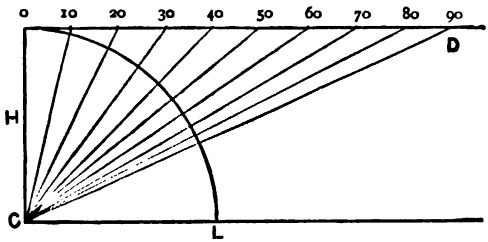
It may be of service to some if we refer here to the manner in which this tangent scale is constructed.

Let the quadrant O L (fig. 58) represent a portion of the circle along which the scale is to be marked, and let C O be the radius along which the index needle is to point when at rest and when no current is circulating through the coil of the instrument. Then draw the tangent line, O D—that is to say, a line at right angles to O C, meeting it in O. Then mark off along O D any number of

equal divisions, and project lines from these points or divisions to C, the centre of the circle, intersecting the circumference at various places. These points of intersection will then correspond to the equal divisions along O D, and will be proportional to the tangents of the various angles which would be measured at those intersections. This device saves the operator the trouble of ascertaining from a table the tangent equivalents to the various deflections and then calculating their relative values.

A piece of looking-glass is placed under the scale-plate and is exposed at two circular slots in the plate, so that in taking a reading the observer may let the pointer cover its own reflection, when he will be assured that he is looking vertically down upon it, avoiding thereby any error due to parallax—that is to say, any

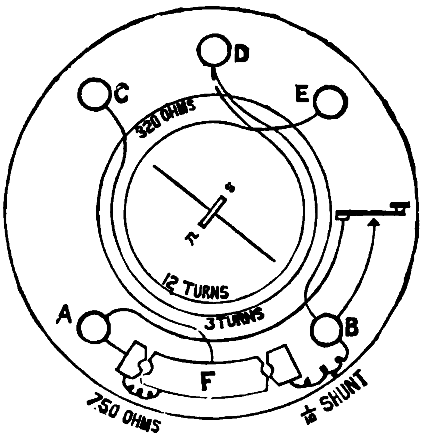
FIG. 58.



inaccuracy in reading caused by looking at the pointer sideways. A lever, operated by a small switch extending through the box which carries the needle and scales, is provided for lifting the needle off its pivot when not in use. There is also a small adjustable magnet which slides on a brass rod over the needle, and is used for varying the sensibility of the instrument. This may appear to be a step backwards from the beautifully simple thesis upon which the instrument is constructed. If there were no very good reason for introducing this 'controlling' magnet to vary the sensibility of the instrument, the wisdom of its introduction would be questionable. But it must be remembered that there are several hundreds of these instruments in use throughout the country, and if it is known that a reading of, say, twenty-five divisions corresponds in every case to a current of 1 milliampere,

the direct value of any other reading can be confidently estimated. The controlling magnet, when placed with its S. pole over the N. pole of the needle, assists the directive force of the earth's magnetism, or helps to keep the needle in the meridian with its north-seeking pole pointing to the north. The effect is the same as it would be were the value of H increased, and a stronger current is then required to produce any given deflection. Hence the sensitiveness of the instrument is reduced. On the other hand, if the controlling magnet is placed with its north-seeking pole pointing northwards, it tends to turn the needle round, and therefore its

FIG. 59.



effect is the same as would result from a reduction of the value of H, whence the sensitiveness of the instrument is increased. Either effect may be varied in magnitude by sliding the magnet up or down the rod. For instance, the needle will move from zero with the weakest current when the magnet is placed at the bottom of the rod with its poles opposing the earth's magnetism.

A reference to fig. 59 will make the conception of the electrical portion of the instrument easier. There are three separate coils of wire in the brass ring, or bobbin, the ends of each being brought down through the hollow pillar and connected under the base of the instrument to their respective terminal

screws, as shown in plan on the figure. Between the terminals C and D is a coil consisting of three turns of thick wire; between D and E are twelve turns of similar wire, but wound in the opposite direction. If the current be sent from C to E, we get nine turns acting on the needle, for three of the twelve turns are neutralised by the three in the opposite direction between C and D. The resistance of these coils is negligibly low, so that we are able to get the effect from three, nine, or twelve turns without varying appreciably the strength of the current. The other coil consists of a great many turns of fine silk-covered wire. Its resistance is exactly 320 ohms. One end of it is joined to terminal B, and the other end to the middle brass block F. By inserting a brass plug in the left-hand hole, the end of the coil attached to the middle block is connected to terminal A direct. If, however, this plug is removed, the current in travelling, say, from B, has to pass through an additional resistance coil of 750 ohms (which is fixed under the base of the instrument) before it reaches terminal A. Under these circumstances the total resistance between A and B is 1,070 ohms. Suppose now a single Daniell cell, whose resistance is comparatively low, and whose E.M.F. is 1·07 volt, to be joined to terminals A and B. By Ohm's law the current is equal to $\frac{1\cdot07 \text{ volt}}{1{,}070 \text{ ohms}}$, or ·001 ampere—that is, 1 milliampere.

These resistances are, in fact, calculated for use with a single Daniell cell as a standard. We can therefore always immediately produce a deflection which we know to be that due to 1 milliampere of current, and find the value of any other current by observing its deflection under similar conditions. A small key is fixed on the base of the instrument; when depressed it connects A direct to B, as will be seen from fig. 59, or, in the usual language, it short-circuits the coils. It is used for checking the oscillations of the needle and bringing it quickly to rest.

It is sometimes required to measure a current so strong that the deflection is inconveniently high. In this case a part of the current may be 'shunted,' or provided with an alternative path, or, more correctly speaking, a by-path, so that only a portion of the current shall go through the galvanometer, the rest going through the shunt. It is necessary, however, to know exactly

what fraction of the total current is passing through the instrument and what through the shunt. If we join the ends of the coil by a shunt equal to it in resistance, then the current will divide equally between the two paths, and only half of the total current will be measured. If the resistance of the shunt be $\frac{1}{9}$ that of the galvanometer, then $\frac{9}{10}$ of the current will pass through the shunt and the other tenth through the galvanometer. In this case, therefore, the total current will be ten times that measured by the deflection of the needle.

The instrument we are now describing is provided with such a shunt; its resistance is $\frac{320}{9}$ ohms, and fig. 59 clearly shows how it may be brought into use by inserting a plug in the right-hand hole, thus connecting together the middle and right-hand blocks. Suppose, when the adjustment is such that 1 milliampere gives twenty-seven tangent divisions, that we insert this tenth shunt, and then with a current of unknown strength obtain eighty-one divisions. The current flowing round the galvanometer is manifestly 3 milliamperes, but this is only $\frac{1}{10}$ of the whole, consequently the total current is 30 milliamperes.

In order to reduce the current flowing through a galvanometer to any fraction of its full value, say, to $\frac{1}{n}$, the resistance of the shunt necessary to produce that result must be $\frac{1}{n-1}$ that of the galvanometer. A moment's reflection, however, will make it evident that the introduction of a shunt reduces the resistance of the circuit, and may, therefore, cause a considerable and material increase in the current strength. Where this inciease of strength is appreciable, the introduction of extra resistance sufficient to compensate for the fall caused by the shunting becomes necessary, the problem being to ascertain exactly how much compensating resistance is required. By the laws of the joint resistance of two parallel wires, explained in Chapter II., the joint resistance of the galvanometer, G, and the shunt, S, will be equal to $\frac{G\,S}{G + S}$. Now, the resistance of S has just been shown to be $\frac{1}{n-1}$ part of G, or $\frac{G}{n-1}$, that is,

if only a tenth of the current is to pass through the galvanometer, the shunt resistance should be $\frac{1}{10 - 1}$ part of the galvanometer resistance G. That is to say, $S = \frac{G}{n - 1}$, and inserting this value we get—

$$\frac{GS}{G + S} = \frac{G\frac{G}{n-1}}{G + \frac{G}{n-1}},$$

which is equal to $\frac{G}{n}$.

So that the joint resistance of a galvanometer coil of 320 ohms and its tenth shunt will be $\frac{G}{n} = \frac{320}{10} = 32$, whence it follows that the reduction in resistance due to the use of the shunt amounts to $G - \frac{G}{n}$, or $320 - 32 = 288$. 288 ohms is, therefore, in this case the resistance that it would become necessary to introduce in order to restore the resistance of the circuit to the same value that it had prior to the introduction of the shunt. And, generally, it may be said that the introduction of a shunt reduces the resistance of the circuit to the extent of $\frac{n-1}{n}G$, and that amount of resistance will need to be inserted to re-establish the conditions of the circuit. In short, this compensating resistance is equal to the difference between the resistance of the galvanometer alone and of the galvanometer shunted.

When great accuracy is desired, all the readings on the tangent galvanometer should be taken with the needle deflected as nearly as convenient through an angle of 45°. The reason for this is, that any given proportional increase or decrease in the strength of the current will produce a greater effect on the needle when it is in that position than when in any other, or, in other words, the sensitiveness of the instrument is then at its maximum. For instance, if, when the needle is deflected through 45°, an increase of the current by one-fortieth gives an increase of one

division in the deflection, a similar increase in the current when the needle stood at 10° or 80° would not be perceptible.

Every galvanometer has a definite *angle of maximum sensitiveness*, or such an angle of deflection that with a given proportional increase in the strength of the current there will be a larger divergence than when the needle is at any other point on the scale. The mathematical demonstration of the existence of this angle would be somewhat beside the scope of this work, but we may repeat that for every tangent galvanometer the angle of maximum sensitiveness is 45°. We should always endeavour, therefore, when using this instrument to get the deflection as near 45° as possible, or when comparing two currents get the deflections at equal distances on either side of this point.

It has already been pointed out that it is very convenient, we would say more, it is necessary, in practice to be able to determine immediately the value in amperes or milliamperes, to which some particular deflection of the needle corresponds, and it will be remembered that with a Daniell cell as a standard a current of 1 milliampere may be immediately produced ; but it must not be forgotten that owing to the alteration in the directive force consequent upon moving the instrument, or moving pieces of iron in its vicinity, it is essential that a standard reading should be taken prior to each test or series of tests. The experimenter should also guard against any such prejudicial effect as would result from a bunch of keys, or a knife carried in the pocket.

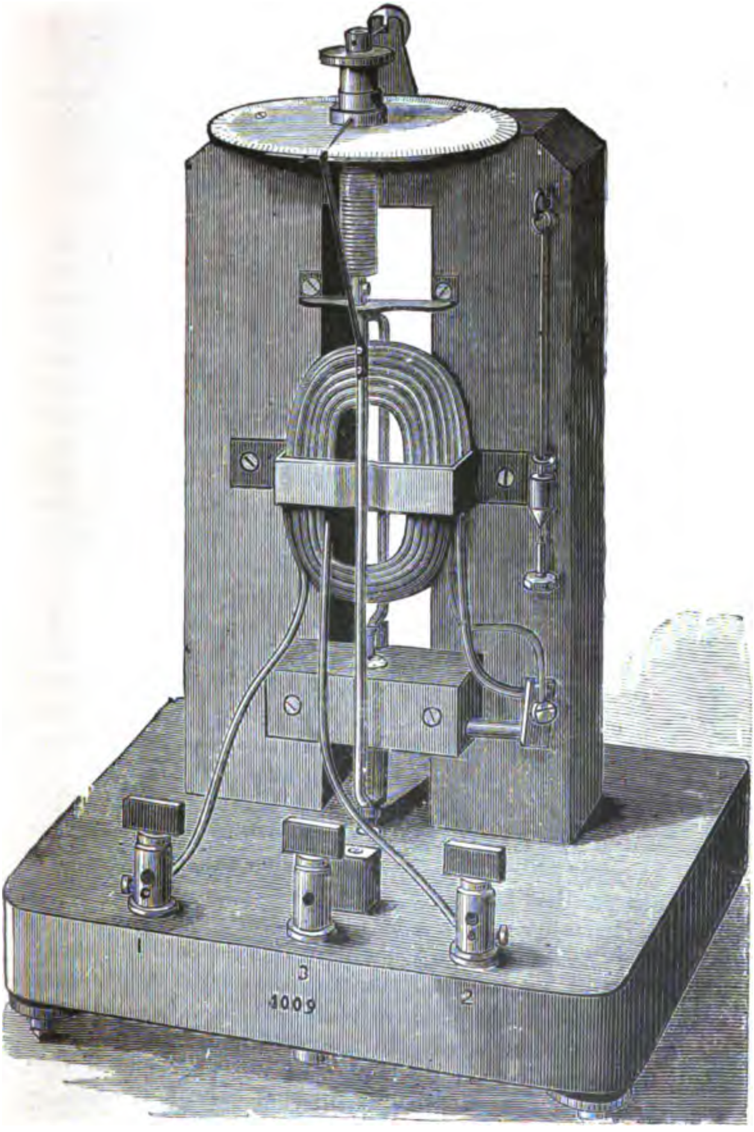
The foregoing applies to a galvanometer with a tangent scale constructed so that its zero point is in the centre, as is the case with the *inner* scale on the tangent divisions side in fig. 57. But it will be seen that in this figure there is an outer scale also of tangent divisions, but with the zero point at the extreme left-hand, where the pointer is shown resting. This outer scale is known as the 'skew scale,' from the position of the needle when at zero, and its great advantage lies in the fact that the range of measurement is double that of the ordinary scale. For a comparatively high reading, also, the deflection can be read with greater ease as the pointer is not in the part of the scale where the divisions are close together. It is true that a small deflection from this zero cannot easily be read, on account of the closeness of the division

marks, but the ordinary scale can be employed for this if necessary.

Unfortunately, the tangent galvanometer is but little suited for the measurement of very powerful currents such as those generally employed in electric lighting. We must, therefore, now direct attention to an instrument which will answer this purpose, and one which is beautifully simple in its conception, and at the same time remarkably accurate and free from error. It is based upon the simple experiment mentioned at the commencement of this chapter, viz., the attraction or repulsion which takes place between two wires carrying currents. It may now be stated that the force of this attraction or repulsion is readily measurable, being, in fact proportional to the strength of one current multiplied by the strength of the other, provided that the distance between the two wires remains constant. If we suppose the currents in each of the wires to be exactly equal, say 2 amperes, then the force may be represented by the number $2 \times 2 = 4$. Now if we double the current strength in each wire, the force of attraction or repulsion will be $4 \times 4 = 16$; so that, when the current strength in each is doubled, the force between them is quadrupled. Similarly, if we treble the current in each wire, or make it 6 amperes, then the mutual force will be $6 \times 6 = 36$, or nine times as great as when the current was 2 amperes. We therefore see that the force of attraction or repulsion between two wires carrying equal currents varies as the square of the current strength. It will be apparent that the simplest method of obtaining equal currents in each wire is to join them in series, and send the same current through both of them in succession. Then, if any number of currents be sent through them, the force of the action between the wires will be proportional to the square of the strength of the current in every case, whence it may be reasoned that if these forces can be measured or compared, the currents producing them can also be estimated; for as the force varies as the square of the current, the current will vary as the square root of the force exerted by it.

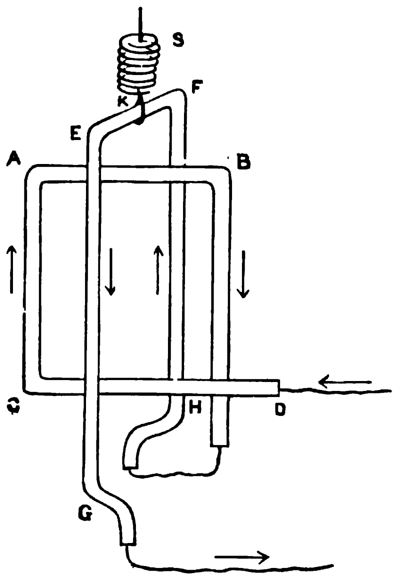
In constructing an instrument on this principle, it is necessary, therefore, to have some means of accurately measuring the force exerted, and also to ensure that the distance between the wires remains exactly the same during all the comparisons.

FIG. 60.



The Siemens dynamometer fulfils all these conditions to the letter. A general view of this instrument is given in fig. 60, fig. 61 showing the manner in which the principle is applied. The two wires (or coils) are rectangular in shape. One of them, A B C D (fig. 61), is rigidly fixed to a vertical support, while the other, E F G H, which is sufficiently large to embrace the fixed wire, when the plane of the one is at right angles to that of the other, is suspended by a stout silk thread.

FIG. 61.



In order that the current may be passed through the movable coil, without in any way impeding or interfering with its freedom of motion, its two ends, G and H, are brought round and bent down into mercury cups placed vertically one over the other, so that the two ends and the point of suspension, K, are in the same vertical line.

Connection with the mercury is made by a wire passing in at the bottom of the cup. The arrows in fig. 61 show the direction of the current in the various parts of the circuit, when a current is sent through both coils in series, and it is easy to see that each vertical limb of the movable coil will be urged, by repulsion on one side and attraction on the other, to set itself in the same plane as the fixed coil. But it has already been said that it is essential that the coils should remain or be brought back into the same relative positions when the force between them is measured. In the Siemens dynamometer the position selected is with the planes of the two coils at right angles; and the force measured is that force which is necessary

to keep the movable coil in this position against the action of the current.

This antagonistic force is applied by means of a spiral spring, S, the lower end of which is rigidly fixed to the rectangle E F G H; while its upper end is fixed to a mill-headed screw, which can be turned round, torsion being thereby applied to the spiral spring. A pointer is attached to the screw-head and moves with it, and, travelling over a graduated scale, divided usually into 400 equal divisions instead of 360 degrees, indicates the amount of torsion applied to the spiral spring in bringing the coil E F G H back to the zero position, against the opposing force due to the current circulating in the coils. It is a simple and well-known law that the force of torsion is proportional to the angle of torsion, and as the angle through which the screw is turned in order to keep the movable rectangle at zero is an exact measure of the torsion applied, the force necessary to the production of that angle must be proportional to the force acting between the two coils, and due to the current circulating in them. This latter force varies, as we have seen, as the square of the current strength, so that, therefore, the current is proportional to the square root of the angle of torsion. The movable coil also carries a pointer, the end of which just overlaps the scale-card and plays between two pins about half an inch apart. When it points to zero, the two coils are accurately at right angles one with the other.

The instrument has usually two separate and distinct fixed coils; one consisting of a few turns of thick wire, and the other of a larger number of turns of thinner wire. The object of this arrangement is to facilitate the measuring of currents differing very considerably in strength, and so to increase the available range of the instrument. One end of the thin-wire coil is joined to the left-hand terminal screw (fig. 60), and one end of the thick-wire coil to the right-hand screw. The other two ends are connected to the upper mercury cup, while the lower cup is joined to the middle terminal screw.

For a very strong current, then, the centre and right-hand terminals, giving the thick-wire and movable coils, should be used; while for a weaker one, the centre and left-hand terminals, between which are the thin-wire and movable coils, should be employed.

On account of the operation of the law of the square, a more accurate reading can be obtained in the higher part of the scale than in the lower, and it is therefore, where possible, more advantageous to use the thin-wire coil for such currents as would give only a low reading with the thick-wire coil.

Three levelling screws are provided, it being absolutely essential that the coils should be exactly perpendicular. The movable rectangle can be raised or lowered by means of the thread which is attached to a screw at the top of the instrument, until it moves quite freely and makes good contact with the mercury. It is difficult to replace this silk thread quickly, and this constitutes a weak point in the instrument, for an inexperienced operator frequently commences his experiment by breaking it.

The instrument requires calibration, that is to say, it is necessary to find out to what current strength a certain amount of torsion is equivalent, before any unknown current can be measured in amperes. This calibration may be effected by deflecting the rectangle by a current of known strength, and then by turning the milled-head attached to the upper end of the spiral spring, applying just sufficient torsion to restore the pointer attached to the rectangle to the zero position. Suppose the current to be one ampere and the torsion applied 16 divisions. Then if a current of unknown strength be sent through the same coil, and it is necessary to apply 64 divisions of torsion to bring the rectangle back to zero, the latter current will be 2 amperes in strength ; for

$$c_1 : c_2 :: \sqrt{16} : \sqrt{64},$$

that is as 4 is to 8 or as 1 is to 2.

In practice such calculations would be exceedingly inconvenient ; the makers, therefore, calibrate the instrument, or determine what strength of current corresponds with the various angles of torsion, both for the thin- and thick-wire coils. These results are tabulated in a convenient form and supplied with the instrument.

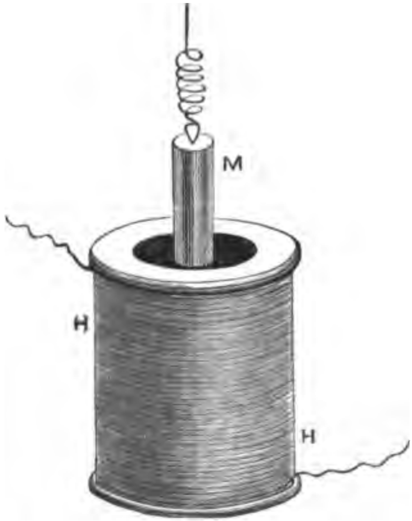
On referring to fig. 61 it will be observed that, if the current is reversed, the rectangle will still be deflected in the same direction, because, the direction of the current in *all* the sections being altered, attraction or repulsion will take place between the same

limbs as before. The instrument can therefore be used to compare either positive or negative direct currents, or even alternating currents—*i.e.* those whose direction is rapidly reversed.

The pointer attached to the screw-head should always stand at zero when the instrument is not in use, otherwise the spiral spring will take up a *set* and will not bring the rectangle to zero when the pointer is brought there. The spring will, however, gradually recover from any such set if it be not excessive.

The Siemens dynamometer is a very accurate instrument when used with ordinary care, but every measurement occupies a certain amount of time, for in every case the rectangle has to be brought back exactly to zero, the amount of torsion noted, and then the table referred to, to ascertain the current strength to which this torsion corresponds.

FIG. 62.



It is evident that an instrument which immediately indicates in amperes the strength of the current flowing is far more convenient to use, although, unfortunately, a *direct-reading* instrument has not yet been designed which may be relied upon for any length of time to be as accurate as the Siemens dynamometer. Instruments of this class are called ammeters, and one of the earliest was that designed by Professors Ayrton and Perry, but although a very good instrument its use is now almost restricted to laboratory and kindred work.

It is based upon the fact, that a piece of soft iron placed in a magnetic field which is not uniform, will be urged from a comparatively weak towards the strongest part of the field. One way of viewing the action is to consider the iron rod, M (fig. 62), as a

magnet for the time being, and then if the field be generated by a current circulating round a helix of wire, H H, and the iron is placed just outside the helix, it will be sucked down until it reaches the middle of the helix, which is the strongest part of the field. Now, this action will be proportional to the product of the strength of the field and the strength of the temporary magnet; but as the latter varies with the strength of the field, but not according to any regular law, the readings will not be proportional to the current strength unless by some means the strength of this temporary magnet is kept constant. Experiment shows that, although the magnetic lines of force pass readily through a piece of iron when there are very few lines already there, yet, when a great many are present, any further addition to their number becomes very difficult. When in this latter condition the iron is said to be 'saturated.' A piece of *very thin* soft iron tubing becomes saturated even in a weak field, that is, in a field traversed by but few lines of force; so that beyond a certain stage, although the strength of the field is increased, the number of lines of force passing through the iron tubing, that is, its strength considered as a magnet, remains practically the same. Therefore, if we use a very thin tube of soft iron, the force with which it is sucked into the helix will, for all fields above a certain strength, depend simply upon the strength of the field and will be proportional thereto, and consequently, also proportional to the strength of the current producing the field.

FIG. 63.

Except for weak currents, then, we may estimate the strength of a current by measuring the pull on such a thin tube of iron placed partly inside a helix. It must not be placed exactly in the middle of the coil, as that, being the strongest part of the field, is the position of rest for the iron.

In the instrument under consideration the method of measuring the pull is unique. It depends upon a peculiar property possessed by a flat spiral spring shaped like a curled-up shaving, as illustrated in fig. 63. If such a spring be stretched while one end of it is fixed, the other end will rotate, and the angle of rotation will be exactly proportional to the amount of stretching, the angle being considerable even for a small extension of the spring.

A reference to fig. 64 will show how these principles are combined in the actual instrument.

The helix fills the space marked W W, and is composed of stout wire offering little resistance, so that its introduction into a circuit does not diminish the current flowing therein. T is the thin tube of soft iron which is sucked down more or less by the

FIG. 64.

current, its lateral movements being prevented by two small brass pins, P and *p*. The former is fixed to a small piece of brass, C, which is fastened to the bottom of the soft iron tube. The spiral spring is placed inside this tube, its lower end being rigidly fixed to C and its upper end to the brass pin *p*. As *p* is also rigidly connected to the screw-head, H, the upper end of the spring cannot rotate, therefore when the tube T is sucked down the

lower end of the spring rotates, carrying with it the tube. The upper end of the tube which projects out of the coil carries a pointer which moves over a graduated scale, and so indicates the angle of rotation, the usual horizontal mirror being provided to avoid errors due to parallax. The scale is divided into equal divisions representing amperes and fractions of an ampere, but as the iron does not become saturated until the current has attained a certain strength, the first portion of the scale is never used, and is, in fact, not graduated, for, as has been explained, the indications at this stage are not proportional to the current strength. It is clear that if the iron tube moved through any considerable distance so as to get into a part of the field of different strength, the readings would not be proportional ; but it will be remembered that the peculiarity of the spring is that the angle of rotation is great for a very small extension in length, consequently the pointer traverses the whole range without the distance through which the iron moves being sufficient to cause inaccuracy. The instrument is calibrated by the maker, similar scale-cards having equal divisions being used for all instruments of the same range, and the adjustment effected by shifting a small auxiliary coil. When a current is sent through the instrument the pointer indicates at once the number of amperes of current flowing, thus avoiding calculation or reference to a table. Occasionally, however, comparison should be made with some reliable standard, such as a Siemens dynamometer, for the instrument is liable to variation after continued use.

The pointer moves in the same direction, no matter in what direction the current is sent through the coils, because the magnetism of the iron tube is also reversed. There is a possibility here of an error being caused by the retentivity of the iron, but as it is so thin and soft its magnetism is readily completely reversed, and no error is introduced from this cause. In order to indicate the direction of the current a small magnetic needle is usually fitted in the base-board, and its blue-coloured end points towards the terminal screw at which the current enters. The pointer can be adjusted to zero by turning the milled head H. The coils and tube are surrounded by an iron casing, which, as will be explained hereafter, prevents any external currents or

magnets affecting the tube and so causing inaccuracy in the readings.

An instrument with a vertical scale is far more convenient since the movements of the pointer can be seen at a distance. A number of such instruments depend upon the power of a coil alone, to raise a more or less weighty piece of iron against the force of gravity, while others have a solenoid and core to perform a similar operation. They all require to be calibrated, but, under

FIG. 65.

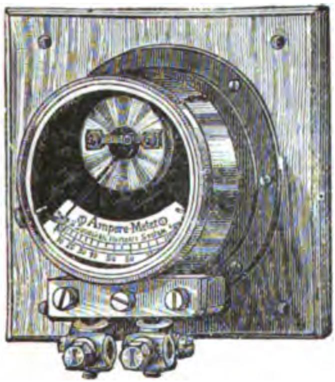
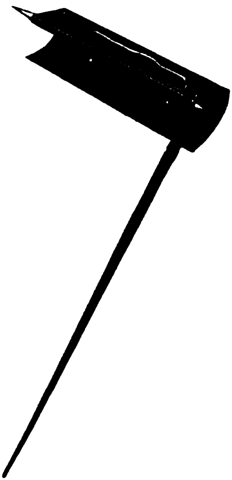


FIG. 66.



the circumstances, that is not objectionable providing the calibration is correctly performed, and that the value of the various readings remains fairly constant for a considerable time.

The first instrument of this class to which we will refer is that constructed by Schuckert. A general view of this ammeter is shown in fig. 65, and a view of the moving portion of it in fig. 66. It will be seen that the instrument is made to be fixed with its base in a vertical position, the working parts being protected by a circular metal case with a glass front. From the two terminal clamps below the instrument case, stout metal bands are led to the solenoid, which is placed with its axis horizontal, and

which when used for very heavy currents consists of single copper casting, with helical saw-cuts, so as to lead the current a few times round the 'needle.' With such a solenoid no insulating material is employed other than the air; but in the case of instruments constructed for the measurement of weaker currents, the solenoid is made of a number of turns of ordinary stout insulated wire. A light steel arbor or spindle is pivoted so as to lie parallel to, and a little to the left of, the axis of the coil. It has attached to it a thin curved plate of soft iron shaped as shown in fig. 66. This piece of iron is nearly equal in length to the arbor, and extends through the length of the solenoid. A light aluminium pointer is also fixed to the arbor at right angles, and the movable parts are so weighted that, in the absence of a current, the pointer is held in the zero position by the force of gravity.

A current passing through the coil of the Schuckert instrument, in endeavouring to rotate the curved piece into the centre, raises it against the force of gravity, through a distance depending upon the strength of the current. The index attached to the arbor travels, therefore, over the scale which is placed behind it, and thus indicates the strength of the current passing through the instrument. As may be imagined, the divisions of the scale are unequal, but the scales of all instruments of the same range are exactly alike, the centre of gravity of the moving parts in each case being adjusted to suit the scale. The adjustment is made by bending a small piece of copper wire (see fig. 66) fixed at one end to the upper side of the arbor, but this operation is a matter of some difficulty when it is desired to reproduce a previous calibration. It is an interesting fact that the gross weight of the moving part is but $\frac{1}{30}$ of an ounce. The amount of friction is therefore very slight, and, there being very little in the instrument which is liable to vary with ordinary workshop usage, it is a useful and practical piece of apparatus.

The instrument known as the 'Gravity' ammeter is the invention of Mr. S. F. Evershed; it is manufactured by Messrs. Easton, Anderson, & Goolden, and is for practical work an excellent and reliable indicator.

In this case also the magnetising coil is placed with its axis horizontal. A small cylindrical piece of soft iron, *a* (fig. 67), is

fixed, by means of a piece of brass, to a brass arbor, this arbor being pivoted at its extremities, and weighted so as to keep the small iron rod in the position shown. F and P are two small soft iron slabs, placed end to end, but just sufficiently far apart for the small iron rod, *a*, to swing freely between them.

The coil encircles these slabs, the arbor, and its attachments ; and when a current passes through it, the lines of force gather up into the slabs, and pass lengthways along them, say from P to F, with the result that there is a comparatively dense field in the air space between their opposing ends.

In its normal position the small iron rod, *a*, lies above and almost outside this dense field, and we have seen that a piece of iron so situated is always urged from a weak part towards the strongest part of the field. Consequently, the iron rod, *a*, is drawn down against the restraining force of gravity which acts on the counterbalancing weight, and, as an increase in the current strength will add to the number of lines and to the force of attraction, the distance through which the iron rod is moved may be made to indicate the current strength. But the depression of the iron rod is not proportional to the increase in the current, consequently an ordinary degree scale, or any other equally divided scale, cannot be employed.

FIG. 67.

It should be explained that, as shown in fig. 68, the two iron slabs (P, F, 67) are fixed upon a stout brass strip, the remote end of which carries a brass disc forming one bearing for the arbor. At the near end of the strip is a larger disc, provided with a hole through which the spindle freely passes, having also fixed to it a smaller brass disc which forms the other bearing for the arbor. Between these two last-mentioned discs is a space sufficient for the pointer to swing freely throughout its range, and a small arm is also attached to the arbor, its end being tapped to fit a small nut which acts as the counterpoise, keeping the pointer at zero when no current is passing through the coils. The scale-plate is vertical, so that the instrument can be placed against a switchboard

or wâll, and its indications conveniently read. The calibration is carefully performed, and a separate scale is made for each instrument, instead of the instruments being adjusted to suit a common scale, with more or less accuracy, as is frequently done.

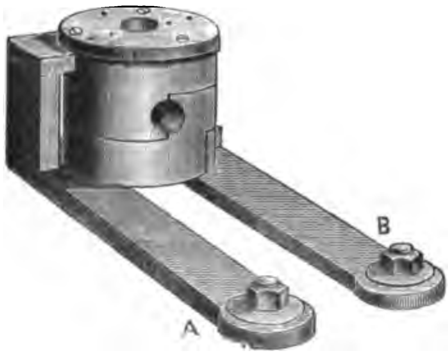
The ends of the iron slabs on the further side, as viewed in fig. 67, are curved slightly, and by altering this curvature, the force with which the iron rod is attracted in any given position can be varied. This enables the scale to be made to suit the work for which the ammeter is intended; for instance, an instrument whose range of measurement is from 20 to 200 amperes may be required for use on a circuit where the working current should never rise above 130 nor fall below 90 amperes, and in such a case it might be necessary to be able to measure exactly the value of the current between those limits, while the upper and lower parts of the scale would simply be used to indicate with certainty the fact of the current being either considerably too high or too low.

FIG. 68.

In such an ammeter the slabs would be so shaped that a given increase in the current strength would move the iron rod through a much greater distance when near the middle of its swing, than an equal increase would move it when it is near either the zero position or the extreme end of its journey. Consequently on calibrating the instrument, we should obtain a scale open in the centre, and closed at the ends —that is to say, with much larger divisions in that part where the most accurate measurements are required to be made. The scale could, of course, if required, be made open at the ends and closed in the middle, or, in fact, varied at any part to suit special requirements. For comparatively low currents the magnetising coil is wound with thick insulated copper wire, but for heavy currents, such as from 200 to 1,000 amperes, a specially constructed coil is employed. If the conductor has any appreciable resistance, such heavy currents develop a considerable amount of heat, and a cotton or silk insulating cover-

ing, besides impeding radiation, is very liable to get damaged. The best insulator is air, which is practically a perfect non-conductor, and indestructible, and has the advantage that it moves away when at all heated, its place being taken by colder air ; the insulating material thus tends to keep the conductor cool instead of preventing the escape of heat, and only in very exceptional cases does the irregular dissipation of heat by the air currents introduce any error. Fig. 69 illustrates the magnetising coil employed to carry heavy currents. It consists of a massive cylindrical tubular casting of copper, the central or axial hole (visible at the top of the figure) being just large enough to admit the brass strip with the slabs, &c., shown in fig. 68.

FIG. 69



It is divided by saw-cuts to form a 'coil.' The current, entering, say, by the straight connecting bar A, passes up the vertical strip to the top of the cylinder, and thence round the coil from back to front. It then passes down to the next convolution at the left of the drilled hole, where this particular saw-cut terminates, and thence round the coil again to the beginning of the third convolution, at the right of, and underneath, the drilled hole. After again going round the coil the current leaves by the bar B. It thus takes about $2\frac{1}{2}$ complete turns round the coil, which, with a current of 300 amperes, would give 750 ampere turns.

It will be evident that such a coil has very little resistance, and that therefore the power absorbed and the amount of heat

developed in it will be correspondingly small. The instrument may consequently be kept continuously in circuit without any risk of damage or serious waste of energy. The bars by which connection is made are long and straight, to prevent the current in the leading wires affecting the 'needle,' for without these precautions a considerable error might be introduced, owing to the powerful currents flowing through the leads. These bars are also shown in fig. 70, which illustrates an ammeter designed to measure up to 1,000 amperes. In this case the 'coil' consists of a massive cylinder divided on one side by a radial saw-cut, and the current makes but $\frac{3}{4}$ of a turn round the needle, thus again giving, with 1,000 amperes, 750 ampere turns.

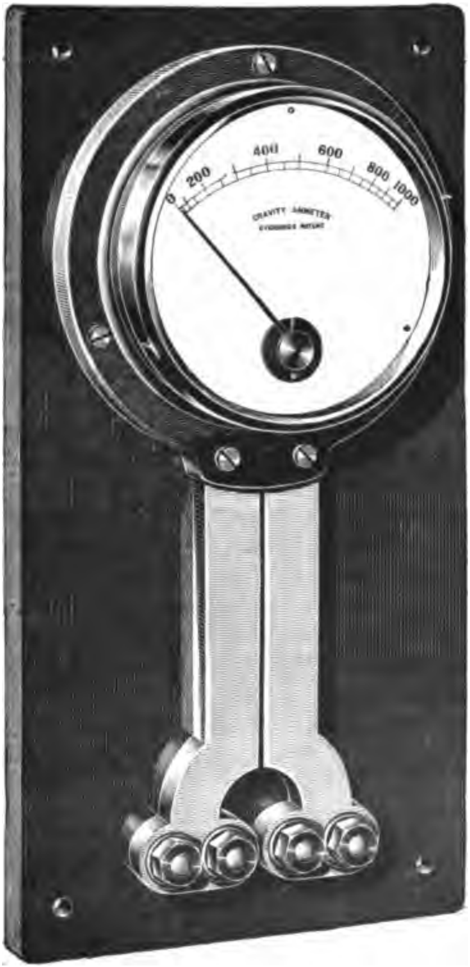
There is one possible source of error with instruments of this description due to the retentivity of the iron, but by exercising great care in the selection and treatment of the metal, this error has been practically eliminated. The iron, in fact, is not touched by a tool after it has been annealed, the film of oxide formed during that operation being simply dissolved by immersion in an acid. Perhaps the best way of testing for inaccuracy due to this cause is to take two sets of readings, one with ascending values of the current from zero to the maximum, and the other with corresponding descending values. Any retentivity of the iron would cause the latter set of readings to be higher than the former, but in these instruments the results are practically identical.

Although it is not so easy to accurately measure a current of several hundred amperes as it is to measure a few amperes or a fraction of an ampere, all these ammeters are calibrated by having their full current passed through them, and its effect, as indicated by the pointer, carefully observed.

The required current strength is obtained by means of secondary batteries, which are charged in series and joined up in parallel for discharging, and in order to insure greater accuracy a definite fraction only of the whole current is measured by the standardising instrument. For example, if it is desired to calibrate an ammeter which is capable of measuring from 40 to 400 amperes, it is joined up in series with the secondary battery, and a set of 100 rather stout iron wire resistances, these wires being all joined up in parallel, and placed so as to have equal facilities for cooling. A standard

ammeter is joined up in circuit with one of these iron wire resistances, and a length of the iron wire equal in resistance to that of the standard instrument is removed, so that this compound branch,

FIG. 70.



formed of a portion of iron wire and the ammeter, is equal in resistance to each of the other 99 branches consisting only of iron wire. This standard ammeter is calibrated with extreme care, and as the main current divides equally among the 100 branches, the instrument accurately measures one-hundredth of it, so that for the maximum current of 400 amperes it is only necessary to measure 4 amperes—a comparatively easy matter. For 1,000 amperes it would thus be necessary to measure only 10; but an ammeter designed to measure such a high current is conveniently calibrated by joining in series with it two 500-ampere meters which are themselves connected together in parallel.

Some thousands of instruments constructed as described are in daily use, but an improved design has been introduced which is even more easily adaptable to all classes of work, and enables any part of the scale to be made open when desired with great ease and certainty.

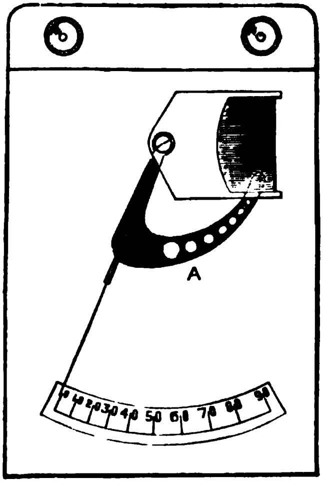
The essential difference is in that part of the instrument which is placed within the coil, and which is now of exactly the same construction for ammeters and voltmeters of all sizes, whether for alternating or direct currents. By reference to figs. 109 and 110 which illustrate the voltmeter, it will be seen that the fixed iron slabs and movable rod are replaced by two curved iron pieces, the outer one being fixed and concentric with the inner one which is mounted on the spindle. When the pointer stands at zero, the inner piece of iron is covered by the outer one, but when a current passes through the coils, the lines of force endeavour to make the magnetic current as good as possible, and in order to effect this they urge the inner piece round towards the position where the two pieces would form an approximately complete cylinder or tube of iron. A counterpoise similar to that in the older type of instrument acts against this magnetic force urging the pointer back to zero. The coil of the instrument with its iron moving part is partly enclosed in a casing of soft iron to shield it from external magnetic disturbances, thus rendering the disposition of the leads connected to the terminals a less important matter than would otherwise be the case.

When such an electro-magnetic ammeter is employed for the measurement of alternating currents the general tendency is for its

readings to be lower than the correct value if it is calibrated to be correct for direct currents, chiefly on account of the eddy currents which are set up in the framework and metal parts in the vicinity of the coil.

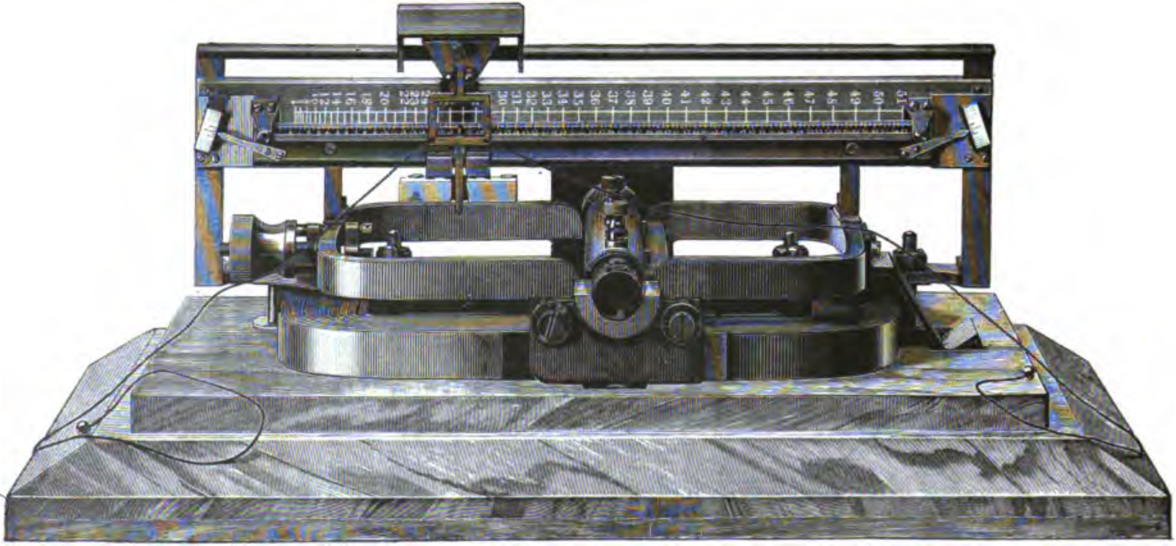
As a matter of fact, it is found that the ammeters under consideration indicate about 2 per cent. lower than the true value of such an alternating current. This error is corrected by permanently shunting the main ammeter coil by a smaller coil of copper wire which is overwound with thin iron wire in order to raise its self-induction to the desired value. The resistance of this subsidiary coil is such that it takes 5 per cent. of the total current when the current is a continuous one, and of course the ammeter is calibrated accordingly to indicate the value of the total current. When the instrument is used to measure alternating currents, the shunt coil takes less than 5 per cent. of the total current because its self-induction is greater in proportion to that of the main coil than is its resistance; and the value given to the self-induction of the shunt coil by overwinding it with iron wire as mentioned above is just enough to reduce its shunting power sufficiently to annul the error of 2 per cent. low reading which would otherwise exist.

FIG. 71.



A simple form of gravity ammeter is that shown in fig. 71, and made by the Société des Téléphones de Zurich. The indicating needle is attached to a peculiarly shaped tongue of very thin soft sheet iron, A, which is furnished at intervals with a number of holes. These holes afford a means of adjusting the sensibility of the instrument and making the scale open near any desired reading. As the current passing through the coil increases in strength the tongue is drawn up into the bobbin and the needle made to pass

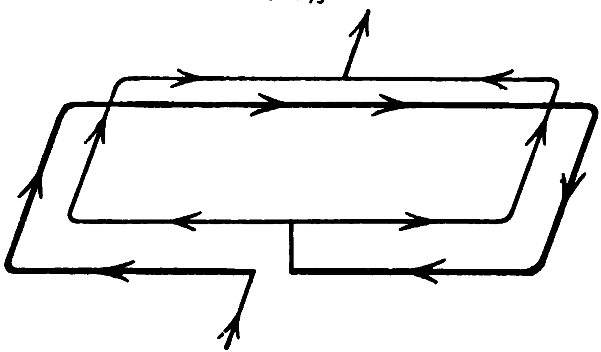
FIG. 72.



over the scale on the face of the instrument. We rarely come across this instrument in practice, but its construction is exceedingly simple, and the principle is so clear that it may be taken as a pattern for laboratory construction.

Lord Kelvin has designed an important series of instruments for the measurement of current strength which are based upon the fact, already discussed in connection with the Siemens dynamometer, that repulsion or attraction takes place between two adjacent conductors carrying currents according to the direction in which the currents respectively flow. These instruments are not suitable for use as ammeters in ordinary practical work, but they are exceedingly useful for accurate measurement in experimental

FIG. 73.



work, and as standards for the calibration and verification of ordinary ammeters. In fig. 72 we illustrate the standard kilo-ampere balance, which is perhaps one of the easiest to understand. It is designed to measure currents from 25 amperes up to 2,500 amperes. The movable conductor is a massive copper rectangle, capable of rocking through a small arc about an axis parallel to the shorter sides. It is placed directly over a second rectangle which is fixed on the slate base, and which for convenience in construction is made up of ten copper strips whose ends are soldered together to form one massive conductor. The principle of the instrument may be gathered from fig. 73, where the arrows indicate the direction in which the current flows in the various parts of the instrument.

It will be seen that the current passes completely round the lower fixed conductor, and then divides at one of the supports of the upper movable rectangle, the two currents meeting again at the second support and passing away thence to the external circuit. It follows that on the left-hand side of the axis of the movable rectangle the currents in the adjacent parts of the movable and fixed rectangles flow in the same direction, hence there will be a force of attraction; while on the right-hand side the currents flow in opposite directions, and consequently the force will be one of repulsion. Both forces therefore tend to tilt the movable rectangle in the same direction, depressing the left- and raising the right-hand side. The rectangle is, however, kept in a horizontal position by means of a weight which slides along a graduated arm, and the current strength tending to deflect the rectangle is deduced from the value of the weight, and its position on the scale when the balance is restored. One of the features of the instrument is the arrangement for conducting the heavy current to and from the movable rectangle without risk of impeding its movements or heating the supports. This is effected by suspending the rectangle from the ends of the horizontal shaft by a large number of short fine copper wires. About 1,600 such wires are employed in the instrument illustrated. The readings being taken when the rectangle is in its zero position, it is only necessary to ensure perfect freedom of motion through a small distance on either side of zero, and this condition is perfectly satisfied by the arrangement adopted.

The next instrument in the series has a range of from 6 to 600 amperes, and it is practically the same as the one illustrated, the main difference being that the ten strips of the lower or fixed rectangle are joined in series instead of in parallel.

In the instruments which are designed to measure still smaller currents the movable portion consists of two circular coils fixed at opposite ends of a beam which rocks about its centre. These coils are connected so that the current flows through them in series and in opposite directions. Each of these coils plays between a pair of fixed coils, one above and the other below it, the current in each upper fixed coil flowing in the opposite direction to that in the lower fixed coil, while it flows in the same direction in the

two lower and the two upper coils respectively. The whole of the six coils are joined in series, and the net result is that the beam is tilted as in the case illustrated in fig. 73, because the right-hand movable coil is attracted from above and repelled from below, while the left-hand coil is repelled from above and attracted from below.

The instruments for measuring the smaller currents have of necessity considerable resistance, and for that reason, if for no other, they are unsuitable for use as ordinary ammeters. But as they are usually employed in series with an ammeter for the purpose of calibration, this high resistance is a matter of little moment.

Some skill is required to effectively use these balances, but a good method of quickly calibrating an ammeter is to first set the balance weight in a position corresponding to a definite current, and then adjust the resistance in circuit until the balance indicates that that exact current strength has been obtained. The position of the ammeter needle for this current can then be noted, and other readings can be obtained in a similar manner. Four pairs of weights are supplied with each instrument, one of every pair being a sliding weight and the other a counterpoise, which is placed in a V-shaped trough at the right-hand end of the balance-arm. A fine vertical line is engraved on a projection from the upper part of the sliding weight which moves in front of the scale, and a magnifying glass being also provided, the exact position of the weight can be determined. In order to move the weight, a sliding platform, which is independent of the rocking part of the apparatus, is pulled either to the right or to the left by means of silk threads, and from a small arm carried by this platform hangs a pendant which engages with the sliding weight when the silk thread is pulled, and releases itself from the weight when the tension on the thread is withdrawn. Different pairs of weights are provided, so that in the event of a particular pair in use being too light to counterbalance the effect of the current then flowing, a heavier pair may be employed.

In the case of the kilo-ampere balance illustrated, the first pair of weights provided corresponds to 5 amperes per division on the scale, the second, third, and fourth pairs to 10, 20, and 50 amperes respectively.

The lineman's detector (figs. 74 and 75) is a very handy instrument when used for tracing circuits and localising faults, but it must not be regarded as a measuring instrument. It consists of two ordinary instrument bobbins, mounted vertically, and each wound with two coils of wire, one consisting of a few turns of thick wire and the other of many turns of fine wire. The former is usually wound to 0·2 ohm, and the latter to about 100 ohms. A shunt coil is sometimes added to the thick-wire coil to reduce its sensitiveness. The magnet is about an inch long, and is mounted on a horizontal axis (see fig. 76), so that it can turn freely inside

FIG. 74.

FIG. 75.

FIG. 76.

the coils, a long non-magnetic indicating needle being also fixed on the front end of the spindle and moving over a graduated dial.

One end of each of the coils is connected to one or other of the outer terminals on the top of the case, the other two ends being both joined to the centre terminal. Constructed as described, the needle should be deflected through 40° or 50° by a current flowing through the thin-wire coil, of 10 milliamperes—that is to say, from a single Daniell cell having an internal resistance of 7 ohms. The thick-wire coil should, with the same cell giving a current of 150 milliamperes, cause a deflection of 20° to 30°.

CHAPTER V.

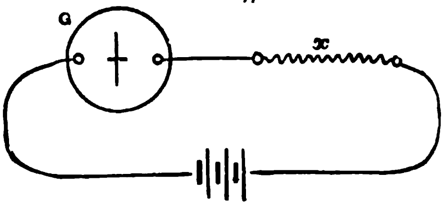
MEASUREMENT OF RESISTANCE

WHEN the difference of potential in volts between the two ends of a wire is known, and also the current in amperes which that difference of potential is able to maintain in the wire, then the resistance of that wire in ohms may easily be calculated, for by Ohm's law it is equal to the number of volts divided by the number of amperes, or $R = \frac{E}{C}$, where E stands for the electro-motive force in volts, C for the current strength in amperes, and R for the resistance in ohms. If, for instance, a difference of potential or an electro-motive force of 15 volts between the two ends of a wire were able to maintain a current of 2 amperes through it, then its resistance would be $\frac{15}{2} = 7{\cdot}5$ ohms. But if the resulting current were only 2 milliamperes, then the resistance would be $\frac{15}{{\cdot}002} = 7500$ ohms. With one or other of the instruments described in the preceding chapter, the current flowing may be measured, and in the next chapter it is shown how the difference of potential between any two points of a circuit may be measured in volts; and this method is perhaps the best that can be devised for finding the value of very low resistances. But sometimes we know, without the necessity for measurement, the maximum difference of potential or electro-motive force which a certain current-generator can produce, and this knowledge will enable us in certain cases to calculate resistance after merely measuring current strength.

If, for example, we have a battery of which we know the electro-motive force, say 10 volts, and also the internal resistance, say 20$^{\omega}$, we may use it to send a current through the tangent galvanometer,

G, and the unknown resistance, x, by joining them all in series as shown in fig. 77. Suppose the resulting current to be 20 milliamperes as measured by the galvanometer, then we may find the *total* resistance of the whole circuit by dividing the electro-motive force by the current. The total resistance will be $\frac{10}{\cdot 02} = 500^{\omega}$. Now, the resistance of the battery and galvanometer is $20 + 320 = 340^{\omega}$, and if we subtract this from the total

FIG. 77.



resistance, we get the value of the unknown resistance, x, that is, $500 - 340 = 160^{\omega}$.

By using the thick-wire coils of the galvanometer, and a battery of very low resistance as compared with that of the unknown resistance, no serious error will be made by ignoring the resistance of the battery and galvanometer, and regarding the unknown resistance as the total resistance of the circuit. Under these conditions a number of fairly high resistances may be easily compared, for the same electro-motive force will send through each a current which is inversely proportional to the resistance. Thus, if with three resistances, a, b, c, we get deflections of 30, 25, and 60 tangent divisions respectively, then, $a : b : c :: \frac{1}{30} : \frac{1}{25} : \frac{1}{60}$,

that is, $$a : b : c :: 10 : 12 : 5.$$

Presuming the galvanometer to be so adjusted that a deflection of 30 tangent divisions is obtained when a current of 10 milliamperes is passed through the thick-wire coil, and the battery employed to have an electro-motive force of 2 volts, then the resistance of $a = \frac{2}{0 \cdot 01} = 200^{\omega}$. Therefore, the resistance of $b = 240^{\omega}$. and of $c = 100^{\omega}$. As previously stated, however, the

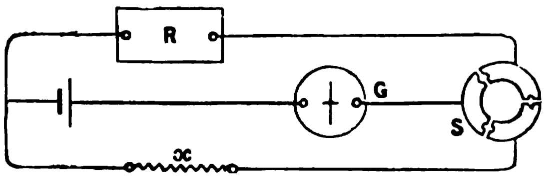
resistance of the battery and of the galvanometer must be taken into account, unless they are very low indeed as compared with the resistances which it is desired to measure.

It should here be observed that in most of the tests to be described it is necessary that a set of resistances whose values are known exactly should be provided. The accuracy of the results obtained depends, in a very great measure, upon the accuracy of the values given to these resistances, so that great care should be exercised in their manufacture, measurement, and use. In Chapter II. some of the principal causes of inaccuracy were enlarged upon, and it was shown how, by avoiding them, a reliable set of resistance coils might be produced.

Assuming such a set of coils to be available, let us now discuss its utility in helping us to ascertain the resistance offered by other conductors.

If a wire, whose resistance we desire to ascertain, is joined up with a battery and galvanometer, the current flowing will deflect

FIG. 78.



the galvanometer needle through a certain angle; let this angle be accurately noted. Then, if the unknown resistance is removed from the circuit, and a box of coils of known resistance inserted in its place, this same deflection may be reproduced by varying the amount of resistance introduced by means of the plugs or arms, as described in Chapter II. The current then deflecting the needle will manifestly be exactly the same in strength as in the first case, and therefore (since the electro-motive force of the battery is unaltered) the total resistance of the circuit must be the same as before. Hence the resistance in the box is equal to the unknown resistance. A convenient way of taking this test is shown in fig. 78. R is the set of resistance coils, x the unknown resistance, and S is a three-way plug switch, consisting of three

pieces of brass, any two of which may be joined together by inserting a brass plug in the holes provided for the purpose between them. By means of this switch, either x or R may be rapidly placed in circuit, and it is advisable to take a second test after R has been adjusted, to make sure that the electro-motive force of the battery has not been altered by polarisation and so have destroyed the accuracy of the test. The galvanometer, G, should be a sensitive one; it should, in fact, under all conditions indicate the alteration in the current strength, caused by the addition or subtraction of the coil of lowest value in the resistance-box. As by this method the same deflection is reproduced, any form of galvanometer will answer the requirements, providing only that it is sufficiently sensitive. It is not necessary to know the resistance either of the galvanometer or of the battery.

Supposing, however, a tangent galvanometer and a battery, both of very low resistance, to be available, the currents which the battery can send through a known and an unknown resistance can be compared directly by the deflections of the galvanometer needle, for if there are, say, 50 tangent divisions in the first case and 45 in the second, and the known resistance is 32 ohms, then

$$45 : 50 :: 32 : x,$$

because the deflection in each case will be inversely proportional to the resistance in circuit. Hence, $x = 35\cdot\dot{5}$ ohms.

When, however, the resistances of the battery and galvanometer are comparatively high, their values must be known or ascertained, and allowed for in accordance with Ohm's law as follows: Let the resistance of the galvanometer, G, be 320^{ω}, that of the battery $r = 12^{\omega}$, and the known resistance $R = 560^{\omega}$; let the current with R in circuit (C_1) give 50 tangent divisions, and the current with x in circuit (C_2) give 45 tangent divisions.

Then, in the first case,

$$C_1 = \frac{E}{R + G + r}, \text{ whence } C_1(R + G + r) = E,$$

and in the second case,

$$C_2 = \frac{E}{x + G + r}, \text{ whence, also, } C_2(x + G + r) = E,$$

therefore $$C_2(x + G + r) = C_1(R + G + r),$$

whence, by dividing and transposing,

$$x = \frac{C_1}{C_2}(R + G + r) - G - r.$$

Since $\frac{C_1}{C_2}$ is merely a ratio, the strength of the currents in milli-amperes need not be known, the number of tangent divisions produced by the currents being inserted instead of C_1 and C_2. Inserting all the values, then, we get

$$x = \frac{50}{45}(560 + 320 + 12) - 320 - 12$$
$$x = 659{\cdot}1 \text{ ohms.}$$

The resistance of the galvanometer is nearly always known and engraved on the instrument, but it is frequently necessary to measure the resistance of the battery at the time of making the test. To avoid this it is better to use a battery of very low resistance, and this may usually be obtained by joining up several sets in parallel.

The equation will then stand :

$$x = \frac{C_1}{C_2}(R + G) - G.$$

By inserting the values as before we can see the amount of the error caused in this case by ignoring the battery resistance of 12 ohms.

$$x = \frac{50}{45}(560 + 320) - 320$$
$$x = 657{\cdot}7 \text{ ohms.}$$

The error is thus but $1{\cdot}3^{\omega}$; and it is not difficult to get a battery of only about 1 ohm resistance to send a sufficiently strong current for the above test, when the error would be negligibly small.

This method also provides us with a means of measuring the resistance of a galvanometer. For, let the second reading be taken through a known resistance $K = 700^{\omega}$ instead of x, then, ignoring the battery resistance, it follows that, as before,

$$C_1(R + G) = C_2(K + G)$$
$$C_1R + C_1G = C_2K + C_2G$$
$$G(C_1 - C_2) = C_2K - C_1R$$
$$G = \frac{C_2K - C_1R}{C_1 - C_2}.$$

Inserting the values we get

$$G = \frac{45 \times 700 - 50 \times 560}{50 - 45} = 700 \text{ ohms.}$$

With the same apparatus the internal resistance of the battery may be measured. For if the battery is joined up to the low-resistance coil of the galvanometer (three or twelve turns), practically the only resistance in the circuit will be that of the battery x. If possible, the adjustable magnet should be placed so that the deflection is, say, 50 tangent divisions. Now, it will be evident that to *halve* the current flowing, the resistance in the circuit must be *doubled*. If, therefore, resistance R is inserted until the deflection falls from 50 to 25 divisions, the resistance R will be equal to the resistance x of the battery.

Sometimes, however, the effect of the controlling magnet is insufficient to produce a convenient deflection, and it is then necessary to introduce some resistance in the first test, say P, for this purpose. Then

$$C = \frac{E}{x + P}, \text{ or } C(x + P) = E.$$

If, now, P is increased to R in order to halve the deflection, and therefore halve the current strength,

then $$\frac{C}{2} = \frac{E}{x + R}, \text{ or } \frac{C}{2}(x + R) = E,$$

therefore $$\frac{C}{2}(x + R) = C(x + P),$$

whence $$x = R - 2P.$$

For instance, if with a low-resistance galvanometer it is found necessary to insert 11 ohms in order to bring the deflection down to 60 divisions, and to increase this resistance to 31 ohms in order to make the deflection 30 divisions, then the resistance of the battery $x = 31 - 22 = 9$ ohms.

In some cases the resistance of a cell is so very low that it becomes a difficult matter to measure it with great accuracy. Secondary cells, especially, have not only a low resistance, but also a comparatively high E.M.F., so that some special method is necessary in dealing with them, if accuracy is desired.

One useful method consists in allowing the cell to send a current through a low external resistance of known value, and then measuring the fall of potential which takes place along this resistance. This fall can be easily found by subtracting the external potential difference from the total E.M.F. developed. As the resistance of each portion of the circuit is proportional to the fall of potential taking place along it, the internal resistance of the cell can then be deduced. One of the hot-wire voltmeters (page 198), designed to indicate up to 2·5 volts, is a useful piece of apparatus for this work. The total E.M.F. of the cell can be measured by joining the voltmeter to the cell terminals, because the high resistance of the voltmeter allows only a feeble current to be generated, so feeble, in fact, that the fall of potential inside the cell is exceedingly low; whence the potential difference indicated is practically equal to the E.M.F. developed. If a second external conductor, but of low resistance, is also joined to the terminals of the cell, the total external resistance will be considerably reduced, and the fall of potential inside the battery proportionally increased, and a lower pressure will be indicated by the voltmeter. Consequently, if we denote the total E.M.F. by E, the fall of potential in the external and internal portions of the circuit by P and p respectively, the resistance of the cell by r, and of the known external resistance by R, it is evident

$$E - P = p,$$

and

$$P : p :: R : r;$$

from which we get

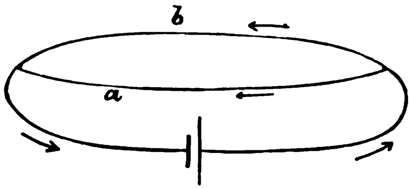
$$r = \frac{p\,R}{P}.$$

When a battery of such cells is to be measured—say twenty—it is better to reverse nearly half of them—in this case, nine; then the resistance to be measured is that of twenty cells, while the E.M.F. urging a current through them is that of only two cells.

The method next to be described depends upon the fact that if two conductors of exactly equal resistance are joined up 'in parallel' and placed in a circuit, as shown in fig. 79, the current will divide equally between the two—that is, the current in *a* will be exactly equal to the current in *b*. The converse of this holds

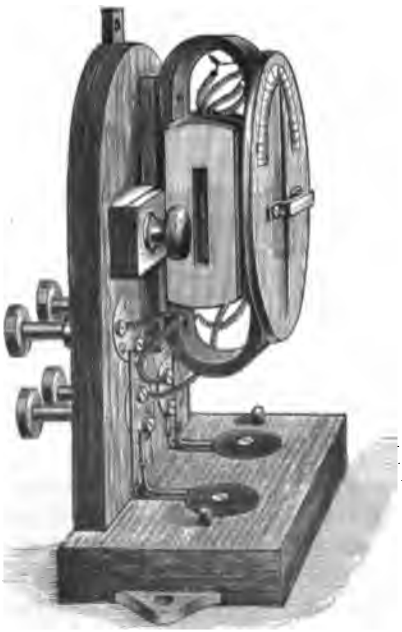
good, viz. if we have two conductors so joined up in parallel, and we know that the current in *a* is exactly equal to the current in *b*, then we are certain that the resistance of *a* is exactly equal to the resistance of *b*.

FIG. 79.



The 'Differential Galvanometer' is an instrument for showing when the currents in two branch circuits are equal. In principle it is very simple. It consists of a magnetic needle, either pivoted horizontally or vertically, surrounded by *two* distinct coils of wire of exactly equal resistance, and wound so as to act with equal force on the needle. If, therefore, a current is sent through one coil, and a current of equal strength is at the same time sent through the other *in the opposite direction*, their effects will be neutralised one by the other, and the needle will not be deflected. Figs. 80 and 81 illustrate a really good form of differential galvanometer, for ordinary work, which is used in the telegraph service.

FIG. 80.

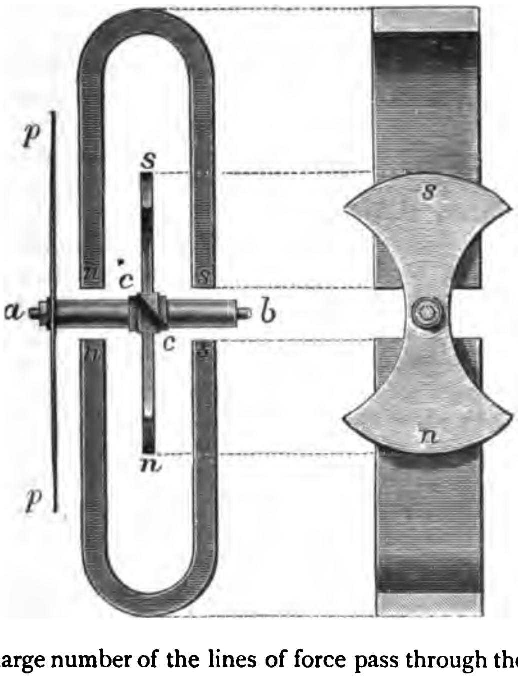


The soft iron needle is vertical, but the arrangement for keeping it strongly magnetised is somewhat peculiar.

Fig. 81 shows side and front elevations of the needle and

magnets. The spindle, which is pivoted at *a* and *b*, is rather massive, and a piece of brass is inserted obliquely at *c c*, as shown, thus breaking its magnetic continuity. Each half of the needle, *n s*, is fixed at right angles to one half of the spindle at this point, and the whole is embraced by two horse-shoe magnets, placed with their like poles adjacent, as shown in the figure. These magnets form a very strong field in the space in which the spindle

FIG. 81.



lies. A large number of the lines of force pass through the spindle, but when they reach the break in the iron at *c c* they bend upwards through the soft iron needle from one side, and downwards from the other side, the result being that the needle is magnetised with its north pole downwards. On one end of the spindle is fixed a blackened brass pointer, *p p*, which, passing over or in front of a circular dial divided into degrees, indicates the movements of the needle. The two wires, each offering 50ω resistance, are wound side

by side over two separate bobbins, so that the corresponding portions of each wire are equally disposed in relation to the needle and exert equal magnetic effects upon it. This method is, of course, far in advance of the old instrument-makers' method of winding one wire alone on one bobbin and the other on another bobbin. The tests for a differential galvanometer are that, if powerful but equal currents are sent in opposite directions through the coils, no effect should be produced upon the needle: each coil used separately should produce equal but opposite deflections with the same current, and the coils should offer exactly the same resistance. The inner ends of the two wires on the bobbins are respectively joined together and the other four ends connected to as many terminals on the back of the instrument. This allows the current to be sent through the coils in several ways. First through one coil only, resistance 50$^\omega$. Secondly, through both coils in series in such a direction that they act upon the needle in the same manner, when the resistance will be 100$^\omega$ and the deflective action doubled, provided the increase of resistance does not sensibly reduce the current. Thirdly, through both coils in parallel and in the same direction; the resistance in this case will be 25$^\omega$, and the deflective action the same as that of *one* coil only. Fourthly, through both in parallel, but in opposite directions, when the needle should, as already stated, be unaffected. Lastly, through both coils in series in opposite directions, when the needle should also be unaffected. This last method of joining up is also useful for proving if the deflective effects of the two coils are equal, for the same current passes through each irrespective of their resistance.

Although the wires are wound side by side throughout, it is very rarely that they are found, in making up the instrument, to act with equal force on the needle. There are three ways of attaining this result without affecting the resistance. The position on the bobbins of a portion of either or both of the wires may be altered; or a part of the wire which has the greater effect may be unwound and wound back on the bobbin in the opposite direction; or the stronger may be unwound until an exact balance is obtained, when the length so unwound may be coiled up in the base of the instrument, where, if wound 'double,' it will have no effect on the needle.

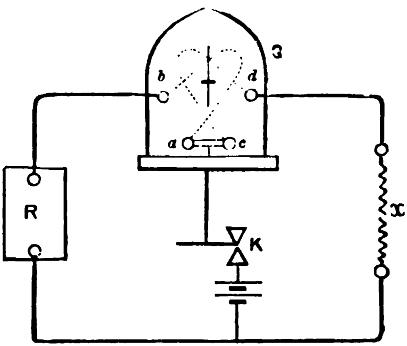
The lower half of the needle is made heavier than the upper, to keep it in the vertical position and to restore it to that position on the cessation of the current; and the current acts against this greater weight when it deflects the needle. The *arm* at which this weight acts increases with the deflection of the needle, so that the angle of deflection cannot be simply proportional to the current strength. The relation between the current and the deflection is, moreover, irregular in consequence of the peculiar shape of the needle (shown in fig. 81), and the proportional deflection diminishes with an augmentation of the current, not only because of the increased effect of the weight, but also because the field due to the current, although almost uniform inside the coil, is far from being so near the edges and just outside.

But at present we shall only consider the use of the instrument with the needle at or near zero, at which point, it may be mentioned, it is most sensitive.

Provided with this instrument, a battery, and a set of resistance coils of sufficient range, we are in a position to rapidly measure unknown resistances.

Fig. 82 shows the best way of making the connections. G is the galvanometer, R a set of resistance coils, x the unknown resistance, and K a key for closing the battery circuit. On depressing the key, the current will divide at $a\,c$, the junction of the two coils of the galvanometer, part passing through the coil $a\,b$ and R, and the remainder through the other coil $c\,d$ and x, back to the battery.

FIG. 82.



Supposing R to be of less resistance than x, then a greater part of the current will pass through $a\,b$ and R than through $c\,d$ and x, consequently the needle will be deflected to one side. By increasing R this excess of current will be diminished, and the deflection of

the needle also decreased, until the needle again stands at zero. Then the currents flowing through both coils of the galvanometer are equal, and therefore the resistance of both branches must be equal, that is to say,

$$x + 50^{\omega} = \text{R} + 50^{\omega},$$

that is, $$x = \text{R}.$$

By further increasing R, the needle would be again deflected, but in the opposite direction to that previously obtained.

Before making a test it is advisable to find out and note in which direction the needle is deflected when R is too large or too small, so that immediately the needle moves to one side or the other, we may know whether it is required to decrease or increase R.

It may be necessary to measure resistances which are either higher or lower than any which can be inserted in the box R. The range can then be extended by shunting one coil of the galvanometer—say by a wire one-ninth of the resistance of the coil. Then, as only one-tenth of the current in that branch will pass through the galvanometer coil, a balance will be obtained when the total resistance in that branch is one-tenth of the resistance of the other. For instance, suppose the coil of the galvanometer connected to R to be so shunted, and a balance to be obtained, when the resistance in R amounted to 650^{ω}; then the unknown resistance would be $6{,}500^{\omega}$ nearly. We say nearly, because, in order to obtain a perfectly accurate result, compensating resistance must be inserted to make the resistance of the shunted galvanometer coil equal to 50^{ω}, as explained in the preceding chapter.

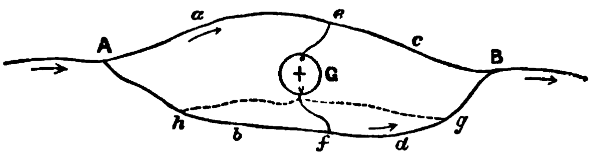
In measuring electro-magnets or any single wound coils, a sudden jerk of the needle, due to self-induction (see Chapter VII.), will always be noticed on making and breaking the circuit. In such cases care should be taken to see that the needle rests at zero when no current is flowing, and then the key should be depressed and the adjustments made with a steady uninterrupted current until the needle again comes to zero.

The differential galvanometer, although a first-rate instrument for comparing two resistances by the equalisation method, loses in simplicity and rapidity when shunts have to be used and allowed for.

By means, however, of a piece of apparatus known as the 'Wheatstone Bridge,' the value of any resistance can be readily measured. The principle of this invaluable apparatus is very simple, and is explained by the diagram (fig. 83). Let us suppose two wires, A *a c* B and A *b d* B, either equal or unequal in resistance, to be joined up in parallel and a current sent through or divided between them, as shown in the figure. The current will, as already explained, divide itself between the two wires inversely as their resistances, but, for our present purpose, the current strength is a matter of little or no importance.

If, now, one terminal of a galvanometer, G, is joined to any point, *e*, in one wire, and the other terminal to a point, *g*, in the

FIG. 83.



other, very near to the junction B, a deflection of the galvanometer needle will be observed, indicating a current flowing from *e* to *g*.

On removing the galvanometer wire from *g* and joining it to another point, *h*, also in the second wire, but very near to A, the galvanometer will again indicate a current, but flowing in the reverse direction, viz. from *h* to *e*. If contact were successively made at points along the wire A *b d* B farther from A, the current would become feebler and feebler until, finally, a point, *f*, would be found at which the needle would not be affected at all, showing the absence of a current through the galvanometer.

There can be but one explanation to these experiments. It was clearly laid down and demonstrated in Chapter II. that whenever a current of electricity flows, it invariably does so in virtue of a difference of potential between the extremities of the conductor through which it flows, and, conversely, whenever the extremities of a conductor are at different potentials a current flows through it. These two facts must never be lost sight of, for they constitute the key to a host of electrical phenomena and problems. Inasmuch,

then, as it was seen, by the evidence of the galvanometer, G, fig. 83, that a current passed through it when its terminals were connected to the points *e* and *g*, and to the points *e* and *h*, the currents flowed as a consequence of differences of potential between the respective points. And the absence of a current on connecting the points *e* and *f* together is an equally clear proof that those two points were at the same or equal potentials. If we suppose A to be at a higher potential than B, and connect the galvanometer directly to those points, so that it shall share the current arriving at A, the needle will be deflected to one side or the other, the particular deflection being governed by the direction of the current round the needle. Let us suppose the deflection to be to the right. Then, on connecting the galvanometer to A and *g*, or even to *e* and *g*, the deflection will also be to the right, and will establish the fact that the potential at *e* is higher than that at *g*. On the other hand, the opposite deflection which is obtained when the galvanometer is connected to *e* and *h* affords ample proof that the potential at *h* is higher than that at *e*. Now, as the ends of the two wires connected at A are always at the same potential, and as the ends at B are also at the same potential, although lower than that at A, it follows that the fall of potential along A *a c* B must equal that along A *b d* B. It also follows that if we fix upon any one point in either of the wires, there must always be a point somewhere in the other wire which will be at exactly the same potential, and if these two points are connected together no current can possibly flow between them. Herein is the underlying principle of the Wheatstone bridge.

We must now endeavour to discover what relation, if any, exists between the resistances of the four sections into which these wires are divided. Let the resistance of the section between A and *e* be denoted by *a*, that between A and *f* by *b*, between *e* and B by *c*, and between *f* and B by *d*.

The difference of potential between A and *e* is equal to that between A and *f*; call this P_1.

Again, the difference of potential between *e* and B is equal to that between *f* and B; call this P_2.

Now we have seen that in every case (since by Ohm's law $E = CR$) the difference of potential between any two points is

equal to the current flowing, multiplied by the resistance of the conductor between those points.

Suppose the current flowing in the upper branch, A *e* B, to be C_1, and that in the lower branch, A *f* B, to be C_2.

Then $$P_1 = C_1 \times a;$$

also $$P_1 = C_2 \times b;$$

therefore $$C_1 \times a = C_2 \times b,$$

or $$\frac{a}{b} = \frac{C_2}{C_1}.$$

Again, $$P_2 = C_1 \times c,$$

also, $$P_2 = C_2 \times d,$$

therefore $$C_1 \times c = C_2 \times d,$$

or $$\frac{c}{d} = \frac{C_2}{C_1}.$$

But $\frac{a}{b}$ has also been shown to be equal to $\frac{C_2}{C_1}$;

consequently $$\frac{a}{b} = \frac{c}{d}$$

This is the relation between the resistances which we sought to discover, and we might, in the same way, prove that it holds good for other cases where the resistances have different values on account of the galvanometer connections being made at different points.

The relation may also be viewed from another standpoint. The fall of potential along a conductor is proportional to its resistance, and, conversely, the resistance of a conductor is proportional to the fall of potential which takes place along it. Now, the total fall of potential along the two branches (fig. 83) is equal in amount, and the potential at *e* is equal to that at *f*; and the fall along *a* is equal to the fall along *b*, and also the fall taking place along *c* is equal to that along *d*. Therefore, the value of the resistance *a* bears to that of *c* the same ratio as does *b* to *d*, that is,

$$a : c :: b : d,$$

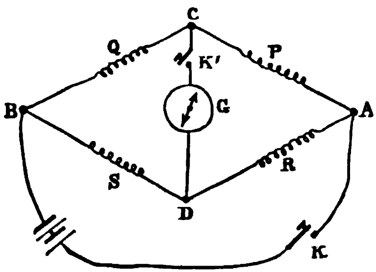
and therefore also $$a : b :: c : d.$$

If one of these resistances, say c, were unknown, and the other three known, we could readily determine the value of c, for $c = \frac{ad}{b}$.

This is, in fact, the method by which resistance is measured with the Wheatstone bridge.

We have in practice four resistances, P Q R S, one of which, say P, is unknown and the others known, and join them up as in fig. 84. The junctions at A and B are maintained at different potentials by means of a suitable battery, but the galvanometer is permanently connected to the other junctions, C and D, and instead of varying the position of the galvanometer connection, D, the known resistances Q R S are varied and adjusted, until the absence of a current through the galvanometer proves C, the junction of P and Q, to be at the same potential as D, the junction of R and S.

FIG. 84.



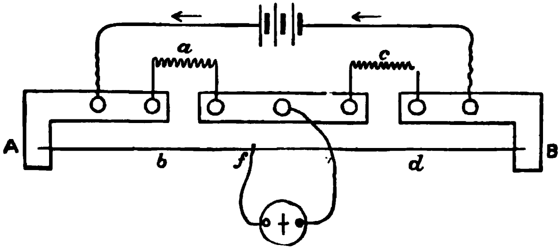
The value of P can then be calculated, as above, the simplest case being when Q = S, for then P = R. Two keys, K and K′, are provided for the purpose of disconnecting the battery and galvanometer circuits respectively.

There are, however, various ways of performing the necessary adjustment of the known resistances; but a very good form of bridge for measuring low resistances may be constructed upon the principle illustrated in fig. 83, where the point of equilibrium was found by shifting one of the wires connected to the galvanometer along A b d B, thus varying the *ratio* of the resistances b and d.

Three brass or copper strips, so stout as to have practically no resistance, are fixed on to a mahogany board, as in fig. 85. Between the ends of two of these strips a wire, A B, is stretched. It is convenient to have this wire one metre in length, with a scale placed under it, divided into a thousand parts. There are three terminal screws on the middle strip, and two on each of the

others. The unknown resistance, c, is connected to the two adjacent ends of the middle and right-hand strips, while a known resistance, a, is joined to the adjacent ends of the other two. A battery is joined up to the outside strips, and a current can thus be sent through the branch a and c, and the branch b and d, in parallel. One end of the galvanometer coil is joined to the terminal screw at the junction of a and c, where the potential will have fallen to a certain amount. The other is connected to a slider which passes along over the wire $b\ d$, and which, when pressed down, makes contact with the wire, and allows the exact

FIG. 85.



point at which contact is made to be read on the metre scale. As previously explained, a point, f, is sought for, at which, contact being made, no current flows through the galvanometer. Then $c = \frac{d}{b} \times a$. It is clear from this equation that $\frac{d}{b}$ is merely a ratio, and need not be known in ohms. If the wire A B is of uniform resistance throughout, it is sufficient to know the length in millimetres of b, and the length in millimetres of d; but the resistance of a must be known in ohms. Supposing a were 2·5 ohms, and a balance to be obtained with the slider at a point 440 millimetres from A; then $b = 440$, and $d = 560$. Therefore $c = \frac{560}{440} \times 2·5 = 3·18$ ohms.

The stretched wire must be of considerable resistance so as to make the fall of potential per unit of length appreciable, and it should be of some hard durable metal, otherwise it would become worn by the slider and its uniformity of resistance destroyed. For

these reasons the wire should be made of German silver, platinum silver, or platinoid. A key should be inserted in the battery circuit, to prevent the current being kept on longer than necessary and heating the wires. Extra resistance in the galvanometer or battery circuits introduces no error, merely reducing the sensitiveness of the arrangement, but it is important to secure good clean connections in the other branches, as any resistance introduced there might cause a great error in the result. To obtain the best results the resistance of the battery should be low and its E.M.F. high ; the resistances in the arms of the bridge should not differ very greatly ; and the galvanometer must, of course, be sufficiently delicate to indicate the difference of potential caused by moving the slider through the shortest measurable distance. But the length of the wire on the galvanometer must not be indefinitely increased to attain this result, otherwise the resistance so added reduces the current in a greater proportion than the deflective effect is increased.

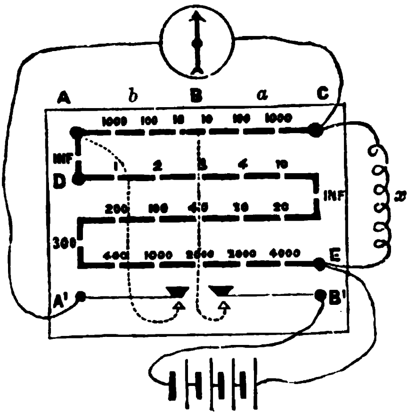
There is, in fact, for every separate test, a certain resistance which it would be best to give the galvanometer. In practice, however, we can do no more than wind the galvanometer in such a manner as will make it best suited to the average conditions under which it will be employed. For an ordinary slide-wire bridge the galvanometer resistance should not greatly exceed one ohm.

FIG. 86.

The slide-wire bridge answers well in a laboratory, where it is exceedingly valuable for measuring low resistances. A more practical form of the Wheatstone bridge, and one which is very largely used for general work, is shown in fig. 86, and its connections in fig. 87.

There is no exposed stretched wire here, but all the resistances are placed in a mahogany box with an ebonite top, their ends being connected to brass blocks fitted with plugs as in the case of any ordinary resistance-box. These resistance coils are measured with extreme care, and the value of each in ohms is marked (often indistinctly, by the way) upon the ebonite. Double terminal screws are employed to avoid risk of resistance being introduced by the careless connection of two wires on to one terminal. In the general view it will be seen that there are two keys, each, when depressed, making contact with a metal stud; these keys are marked A′ and B′ in fig. 87. A terminal screw is connected to each key, and to the right-hand one is joined the zinc pole of the testing battery. The stud under this key is connected beneath the ebonite cover to the brass block B in the middle of the back row of resistances, so that the zinc pole of the battery is joined to this block when the right-hand key is depressed. It is at this point then, corresponding to B, the junction of Q and S in fig. 84, that the current divides, and on either side are three coils of 10, 100, and 1,000 ohms respectively, any or all of which can be inserted at pleasure. At each end of this row of coils is a terminal screw, and the galvanometer is connected to these points. But, as we have seen, it is necessary to have a key in the galvanometer circuit, and it is very convenient to place both keys close together, as shown. One wire from the galvanometer is therefore brought to terminal A′—that is, to the left-hand key—and the stud under this key is connected to terminal A, as shown by the dotted line. Therefore, when A′ is depressed, this side of the galvanometer is joined to terminal A. The other side of the

FIG. 87.



galvanometer goes direct to terminal C. The two 'arms' of the bridge B A and B C correspond to the arms *b* and *a* in fig. 83, and to S and Q in fig. 84, and the arm marked R in the latter figure here consists of a number of coils, ranging from 1 ohm to 4,000 ohms, placed between the terminals D and E. We have thus three arms of the bridge of known values, and the fourth, or unknown resistance, x, is placed between terminals C and E. The copper pole of the battery is brought direct to terminal E, which corresponds to the junction of P and R in fig. 84. Between the arms B A and D E—that is, between the terminals A and D—is a space marked 'infinity.' There is no coil connected to the two blocks at this point, so that the resistance is infinite, that is, the circuit is disconnected, when the plug is removed. This arrangement is exceedingly useful, for it is possible to increase the range of measurement considerably, by removing the plug and inserting an extra box of coils in the circuit here; and further, it is often convenient, in some tests, to be able to separate the coils into two independent sets. There is a second 'infinity plug' between the 10 and 20 ohm coils, and when using the apparatus simply as a set of resistance coils these plugs may be used as keys for disconnecting or joining up the circuit. But this second plug is also useful when employing the bridge in the orthodox fashion. Let it be supposed that it is impossible, by any manipulation of the coils, to establish a balance. Then if a balance is established by removing the infinity plug, it is proved that there is a disconnection in the arm x, or if the deflection obtained is very feeble, it may be taken that the resistance in x is 'above bridge,' or too high to be balanced.

Let us suppose, however, that the bridge has been properly joined up, with an unknown resistance x, the value of which it is desired to find, between C and E.

It is clear that A and C are the points which we want, by adjusting the various resistances, to bring to the same potential, and the galvanometer is connected to these points so as to indicate when this result is attained. We begin by inserting some resistance in the arms B A and B C, say 100 ohms in each. These resistances are not again altered during the measurement, but the adjustment is made by varying the amount of resistance in the

arm D E until the galvanometer shows that a balance has been obtained. When this happens the value of the unknown resistance, x, is equal to the amount which has been inserted in the arm D E. Much time may be saved and greater accuracy ensured by taking a test methodically, and the following points should be attended to. Before starting it should be ascertained that the plugs are firmly in their places and that all the connections at the terminals are good, and to ensure this it is advisable to take advantage of the double terminals provided, and place only one wire on each screw. The galvanometer having been placed in a position convenient for the experimenter, some coils in each of the three arms must be put into circuit, the amount in the arms D E being made as near the unknown resistance as can be guessed. The right-hand key should be depressed and then, a moment afterwards, the left-hand key, and the galvanometer observed; probably the latter will indicate the passage of a current, and it should always be found which way the needle moves when the resistance in the arm D E is, say, too high. If that is done, one can see, immediately the needle moves, whether it is necessary to increase or reduce the resistance in D E in order to get a balance. This is much quicker than obtaining the balance at random. The galvanometer key must only be lightly tapped so as to just indicate in which direction the resistance must be varied, until a balance is nearly obtained, when it may be held down for a longer period. This prevents a heavy current being passed through the galvanometer; and the student will hardly require to be warned that if the battery is kept on too long the bridge coils will become more or less heated and their resistance varied. It should also be borne in mind that with a very delicately made instrument a suddenly applied heavy current is likely to injure the needle or the pivot.

We considered above the simple case when the resistances of the arms B A, B C were equal, but the bridge is not always used under these conditions.

If, for instance, the unknown resistance is comparatively low and we desire to measure it to within a fraction of an ohm, it is then necessary to have these arms of unequal resistance; we should, in fact, make B A 100 ohms and B C 10 ohms. Then, if a

balance were obtained with 13 ohms in D E, x would be equal to 1·3 ohms. For, by the principle of the bridge,

$$x = \frac{BC \times DE}{BA} = \frac{10 \times 13}{100} = 1 \cdot 3.$$

And by using 1,000 ohms in B A and 10 in B C, measurements to within $\frac{1}{100}$ of an ohm might be made.

When the unknown resistance is very high, then the ratio must be reversed, taking, say, 10ω in B A, and 1,000ω in B C. If, now, a balance is obtained with 1,309 ohms in D E, then

$$x = \frac{1000}{10} \times 1309 = 130900 \text{ ohms.}$$

When using this ratio it is not always possible to obtain a perfect balance and so determine the unknown resistance exactly, because the lowest unit in the arm D E is 1 ohm, and this is equivalent to 100 ohms in the unknown resistance. For instance, if in the last test the unknown resistance were 130,925 ohms, it would be necessary to increase the resistance in D E by a quarter of an ohm in order to get a perfect balance, and this fraction is not at our disposal. A supplementary set of resistances having fractional values may be inserted between the terminals A and D, provided that the arrangement is sufficiently sensitive for the galvanometer to respond to the change produced by these fractions of an ohm; but for general work it is sufficient to know the value of a very high resistance to within 10 or 20 ohms, and this can always be estimated by observing the movements of the needle when the resistance in D E is less than 1 ohm too high and less than 1 ohm too low.

It may be remarked that the efficiency of the Wheatstone bridge is reduced by the injudicious choice of a battery, more frequently than by any other cause.

The point to be borne in mind is, that a considerable fall of potential is necessary along the arms of the bridge, that is, between the points A and B in fig. 83. The greater the difference of potential between these points, the greater will be the effect on the galvanometer needle for a given change in any of the resistances, and therefore the higher the degree of accuracy to which we can measure. Now, suppose the bridge to be of the slide-wire form, and the resistance of the arms between A and B to be 2 ohms.

If we employ a battery of 10 Daniell cells, having a resistance 0.5 ohms per cell, the potential difference between A and B will be considerably less than three-quarters of a volt, all the rest of the fall taking place inside the battery. A single Grove cell, having a resistance of ·2", could maintain about 1·8 volt under similar conditions, although its E.M.F. is only one-fifth of that of the Daniell battery. This clearly shows the evil effect of resistance in the battery, and it is evident that when the resistances in the bridge are low, the battery employed, while having a sufficiently high E.M.F., must have a very low internal resistance. When, however, the resistances are high, resistance in the battery circuit is not so harmful (as the fall of potential in any part of a circuit is directly proportional to the resistance of that part), and a battery of Daniell cells may perhaps with advantage be employed; for, as a rule, the internal resistance of a battery of Daniell cells is so high, that even when short-circuited the current is but a fraction of an ampere. But the E.M.F. of the battery is often kept unnecessarily low to avoid a strong current heating the coils; there is, of course, a limit, but by a skilful manipulation of the keys provided, the time during which the current need be kept on is so very short that the heating is inappreciable. We have remarked that it is better to depress the battery key first, and allow the current to become steady before tapping the left-hand key and throwing the galvanometer in circuit. A very short time is sufficient for this, but extra care should be taken that it is done when the unknown resistance is an electro-magnet, or any coil which is liable to the phenomenon of 'self-induction' (see Chapter VII.), or when it has any 'electrostatic capacity,' as in the case of a telegraph line or cable, otherwise the needle will move violently, although the actual resistance may be truly balanced. To enable the student to understand how the nature of the resistance can cause the potential at any two points to be widely different when the current is starting or stopping, and yet equal when it is steady, we may employ an analogy. Suppose we have two equal iron water-pipes joined up as in fig. 83, with some piece of apparatus to indicate a difference or equality of pressure, in the place of the galvanometer, the points *e* and *f* being at equal distances from A or B. Then, the pipes being equal in all respects, the pressure at

e will always be equal to that at *f*, no matter how the difference of pressure at A and B may be varied. If, now, one branch, A *f* B, is replaced by a very flexible india-rubber pipe of similar dimensions, this no longer holds good. Suppose the pipes to be empty and then water at a high pressure to be forced in at A; the pressure at *e* will rise quicker than at *f* because the flexible pipe expands, and this occupies a short time. When the expansion has reached its limit the pressures at *e* and *f* are equal, but on suddenly stopping the flow at A, the pressure at *f* remains higher than at *e* for a brief moment owing to the contraction of the pipe.

Somewhat similarly, as we shall see later on, a current of electricity can never rise to its full value, nor die away, instantaneously; for this reason, the coils of the bridge are so wound that in them the rise or fall is very rapid, and when the unknown resistance is such that the rise or fall takes place at a different rate, the current must be allowed to become steady before the second key is closed.

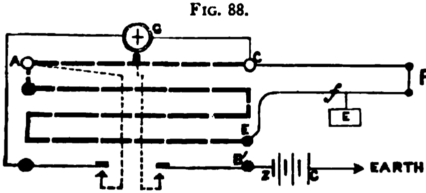
The peculiar method of winding the bridge coils is also useful in preventing any direct action, which might be caused by the current circulating in them, being produced upon the galvanometer needle. When an electro-magnet is being measured, the galvanometer must be placed far enough away to avoid its being affected when the current is passed through the electro-magnet. When there is any reason to suppose that some such effect as this exists, the battery key should be closed and opened several times, the galvanometer key being left open and the needle watched. If it moves at all, we have proof positive that some portion of the apparatus is producing a disturbing effect upon the galvanometer.

When both ends of the unknown resistance are not easily accessible—that is to say, when it is impracticable to bring both ends of the conductor to the bridge—the test may be made by joining one end to the terminal C, and connecting the distant end to earth. The terminal E—that is, the junction of the arm D E—and the copper pole of the battery are also put to earth, and then the test can be made in the usual manner, because the two earth-connected points are at the same potential, and behave in precisely the same way that they would if they were joined to a common terminal.

A leakage sometimes occurs in a covered wire or cable, which allows more or less of the current to escape to earth, provided some other point of the system is also earthed. It is necessary to be able to determine the distance of such a 'fault,' or point of leakage, and this might easily be done by disconnecting the line beyond it, and then, treating the fault as an earth, measuring the resistance of the wire up to this earth as described above.

It rarely happens, however, that any fault develops which does not offer considerable resistance to the passage of the current to earth, and as the amount of this resistance is never known it cannot be allowed for. Further, the resistance frequently varies so rapidly that it is not possible to obtain a balance at all, and some different arrangement of the bridge is necessary. We have seen that in the battery circuit extra resistance, and even variable resistance, causes no error in the result, although it reduces the sensitiveness of the bridge; and if this variable earth fault can be placed in the battery circuit, we can ignore its resistance altogether. This can readily be done if both ends of the wire are accessible; if not, it is necessary to have a second or return wire, and connect the distant ends of the two together. This arrangement is known as the 'Loop test' and is shown in fig. 88. The copper pole of the battery is put to earth, the zinc pole being always joined to line in fault-testing, as the current in that direction—usually by an electrolytic effect—decreases the resistance of the fault. E P is the faulty wire, the fault being shown at *f*. C P is the sound wire by means of which we reach the other end of the faulty wire, the two being looped together at P. The good wire is joined to terminal C, and the faulty one to E. On depressing the battery key the current flows through the bridge and the lines, finding earth at the fault, and a balance can be obtained in the usual way. Let R be the resistance inserted in A E, and let x represent the unknown resistance of the faulty wire from E to the

FIG. 88.



fault at f. Then the total resistance of this arm of the bridge is $R+x$. The other arm consists of the sound wire, C P, and that portion of the faulty wire from P to f. Let the total resistance of this arm be called y. Let a be the resistance in B C, and b that in B A, then

$$a : y :: b : R+x,$$

that is,
$$y = \frac{a}{b} \times (R+x) \quad . \quad . \quad . \quad . \quad . \quad (1).$$

We have here two unknown quantities, x and y, and must therefore get a second simple equation in order to eliminate one of them. It is clear that the total resistance of the two lines is $x+y$, and usually this is known; if not, it can be measured by joining up the bridge in the ordinary way (that is, connecting the copper pole of the battery to terminal E), and measuring the resistance of the loop as that of a single wire without fault; for there will then be no leakage at the fault, as no other part of the system is earthed. Suppose the resistance thus found to be L ohms, then

$$x+y = L;$$

therefore
$$y = L - x \quad . \quad . \quad . \quad . \quad . \quad (2).$$

Therefore, from equations (1 and 2),

$$\frac{a}{b} \times (R+x) = L - x;$$

therefore
$$x = \frac{bL - aR}{a+b}.$$

If we make $a=b$, as is frequently done in this test, then, evidently,

$$R + x = L - x,$$

and
$$x = \frac{L-R}{2};$$

or, we simply subtract the resistance in A E from that of the two lines, and, dividing by 2, obtain the value of x.

Now, x is the resistance in ohms from E to the fault; the length of the wire E P is known, and therefore its resistance per mile, or any other unit of length, is known. Thus we can at once

ascertain the distance of the fault in miles or yards by dividing x by the resistance per mile or per yard as the case may be.

The galvanometer used with the form of bridge above described has a resistance of 800 ohms; it is shown in fig. 89, and is a very good instrument—portable, yet capable of giving evidence of a very small potential difference. When joined up in circuit with a resistance of 20,000 ohms, and a single Daniell cell (the current then being about one twenty-thousandth of an ampere), it will give a deflection of 25°.

Fig. 89.

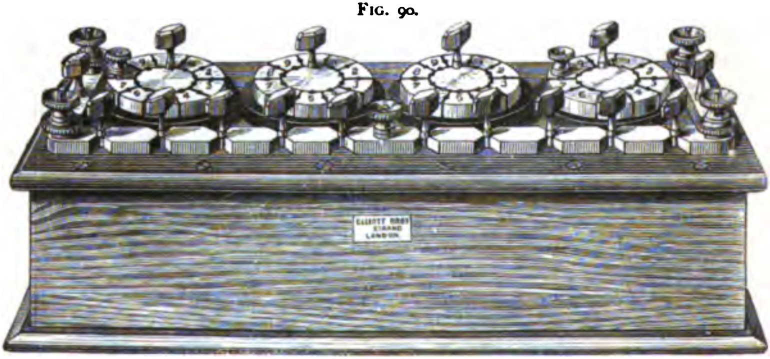
The coil consists of many turns of fine silk-covered wire, wound on a single brass bobbin. The needle, which is pivoted lies exactly in the centre of the coil, and is quite covered by it. At right angles to the needle is fixed a pointer, which projects from the coil, and, passing over a scale and a strip of looking-glass, indicates the slightest movement of the needle. A lever is provided for lifting the needle from its pivot when not in use, and each end of the coil is connected to a terminal which is insulated from the brass casing by ebonite. The features in the design of the instrument which enable it to respond to very feeble currents are the great length of wire employed, the nearness of this wire to the needle, and the excellent pivoting of the needle, which allows it to move easily.

Another form of Wheatstone bridge is shown in fig. 90. This has a very great range, and some of its coils are joined up differently to those in the apparatus last described.

The two 'ratio arms' consist each of five coils, of 1, 10, 100, 1,000, and 10,000 ohms resistance, and are connected up in the usual manner. The arm which is varied in balancing is divided into four sets of coils, each set consisting of nine *equal* coils. The

resistance of each coil in the first set is 1^{ω}, in the second 10^{ω}, in the third 100^{ω}, and in the fourth $1{,}000^{\omega}$. Sometimes a fifth set of $\cdot 1^{\omega}$ each is added. In the figure will be seen 10 brass blocks surrounding a circular central one, with which they can be separately connected by a plug. The block partly hidden by the plug is numbered 0, and this block is connected to the centre of the next dial. Between each of these numbered blocks (except between 9 and 0) one of the equal resistance coils is placed, and by means of the plug any number of them can be brought into circuit. For instance, if the block numbered 5 is so joined to the centre plate, the current passes from the plate by means of the

FIG. 90.



plug, and through five of the coils round to the block number 0, which is joined to the next centre plate, or, in the case of the last dial, to a terminal screw. Some tests can be very quickly made with this form of bridge, and the result seen at a glance, and an advantage results from the fact that only a few and invariable number of plugs are brought into use, thus reducing the liability to error due to a varying resistance between the plugs and the faces of the brass blocks. Of course, as only one plug is used for each dial, the circuit is disconnected in the variable arm every time a plug is shifted.

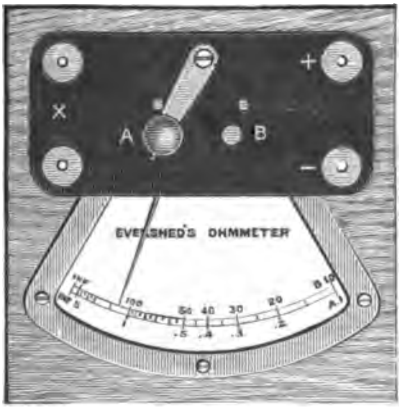
One of the most important uses to which the instruments and methods described in this chapter can be applied, is that of determining the 'insulation resistance' of an electrical circuit, which is accomplished by entirely disconnecting the remote ends

of the conductors, and then measuring the resistance offered by the insulating material to the leakage of the current from one conductor to another, or to earth. Should this resistance fall below a certain prearranged standard, evidence will be afforded of the existence of a fault which requires to be localised and removed forthwith. The insulation of the conductors having been proved, the switches and other fittings may then be joined up, when a second careful test should be made, which in most cases will reveal the fact that the insulation resistance has fallen considerably, often as much as 50 per cent., due mainly to surface leakage. By testing the insulation resistance of the conductors separately, a ready means is afforded of determining whether a particular fault is in the covering of the wire, or in the fittings, and it may be observed that a certain amount of leakage at the fittings should be deemed of less importance than an equal or even a smaller leakage in the conductor covering; for whereas in the former case it is mostly due to moisture and therefore not liable to any serious increase, in the latter case it indicates a damaged or inferior insulating material, a fault which will most assuredly develop under the continued electrical stress.

In electric light installations very heavy currents and rather high E.M.F.'s are frequently employed, which might cause serious damage to life and property should the insulation at any point be allowed to fall below a certain standard or become in any way faulty, and any such fault would, of course, also impair the efficiency of the lighting, to say nothing of the energy wasted. Similar conditions obtain with any system of electrical conductors and fittings for any purpose whatever, and it is necessary that some convenient means should be available for efficiently testing the whole installation, under conditions equally as trying as the maximum stress which it will be called upon to sustain in practice. Especially must the source of electrical power employed for the test be able to develop an E.M.F. at least equal to the maximum intended to be used, otherwise there will be considerable risk that small incipient faults will not be shown up during the test, and will only become manifest when the circuit is in practical use, and when, therefore, the greatest inconvenience, and possibly damage also, will result.

As 100 volts is the lowest E.M.F. which generally obtains in practice, it is evident that the employment of batteries for testing would be exceedingly inconvenient, so much so, in fact, that an efficient test is frequently shirked. A small magneto machine, such as we shall describe in a subsequent chapter, is far more convenient and portable, but it is hardly suitable for use with the apparatus ordinarily constructed for the measurement of resistance. The Evershed 'Ohmmeter' is an instrument which is designed to work with such a machine. It is called an 'ohmmeter,' from the fact that its pointer indicates directly the number of ohms in the resistance under measurement. In practice, however, one does not actually require to find the exact resistance of an installation within a few ohms more or less. It is not possible to measure the higher resistances with certainty to within 100 ohms or so, but this is immaterial, as, if the insulation is below the standard, it matters little whether it is 700,000 or 700,200 ohms. It is, indeed, sufficient if the apparatus can assure us whether, under the stress produced by a sufficiently high E.M.F., the insulation is above or below a certain standard, which we may here suppose to be fixed at 1 megohm. The apparatus can promptly and decidedly indicate whether the resistance is above one megohm or below it, and supposing it to be above, the installation may be passed as satisfactory; but if below this standard, the circuit should be tested in sections until the fault has been localised. A top view of the instrument is given in fig. 91. When the small switch is placed as shown on the contact A, the outer scale A is to be used, but by shifting the switch to the contact B, one of the coils is shunted, thus enabling the lower resistances to be measured by readings on the inner

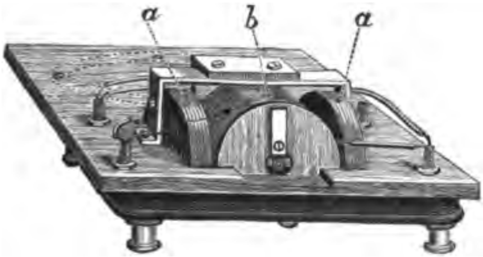
FIG. 91.



scale, B. The wires from the source of E.M.F. (the magneto machine) are attached to the terminals marked + and −, while wires leading from the resistance to be measured are attached to the other terminals marked ×.

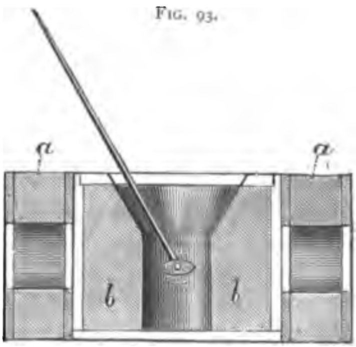
The scale-plate is also shown in fig. 91. The inner of the two scales is marked in divisions of 1,000 ohms from ten thousand up

FIG. 92.



to infinity, while the outer reads in megohms from 0·1 megohm to infinity, the scale being fairly open up to 5 megohms. Fig. 92 is a view of the interior of the instrument turned upside down, the working parts there shown being placed under the ebonite slab on which the switch and terminals are fixed. In the construction of the instrument there are three coils (shown in section in fig. 93); two of them, *a a*, are placed with their planes parallel and are joined in series, while the third, *b*, is placed between and with its plane and magnetic axis at right angles to those of the coils *a a*. The inner coil, *b*, is shaped so as to allow the pointer to travel through a comparatively wide range. Fig. 93, which is also drawn from the under side, shows the small steel needle in its zero position. This needle is then lying in the centre of the coil *b*, and along the common axis of the coils *a a*. In the case underneath it, is placed a small weak bar magnet which adjusts itself so as

FIG. 93.



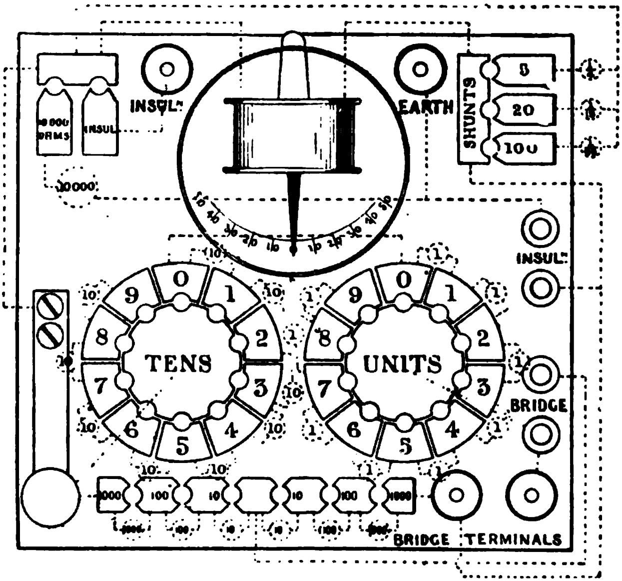
always to neutralise the effect of the earth's magnetism, and, consequently, the only magnetic forces acting upon the needle are those due to the currents in the coils. A current passing through the coils *a a*, which are of high resistance, tends to keep the magnetic needle in the position shown, that is, at zero, with its length along the common axis of the coils *a a*. But its length is then parallel to the plane of the coil *b*, and any current passing through this coil will deflect the needle more or less, its position of rest depending upon the relative strength of the currents in the magnetising coils and the deflecting coil. Now the coils *a a* are connected to the source of E.M.F. only, consequently the current in them, and the force with which the needle is urged to the zero position, is directly proportional to this E.M.F. The coil *b* is connected to the same source of E.M.F. but has the resistance to be measured joined in series with it; this resistance is very high, and the current through *b* which tends to deflect the needle is inversely proportional to it. The deflection of the needle as indicated by the pointer is proportional to the E.M.F. and inversely proportional to the resistance; but as the same source of electro-motive force is used for both branches of the circuit, any variation thereof affects équally the deflecting and the magnetising currents, and, therefore, the deflection of the needle is simply inversely proportional to the resistance to be measured, that of the coil *b* being small.

When the resistance is infinite no current flows through the deflecting coil and the needle remains at zero, but as the resistance is lowered the deflection of the needle is proportionally increased, and it becomes a simple matter to calibrate the instrument so that the pointer shall indicate directly the value of the resistance in ohms or megohms. The ohmmeter, and the accompanying magneto machine which develops an E.M.F. of 120 volts, are enclosed each in a case of 5 inches cube, affording a very compact set for testing at the highest working pressure likely to be adopted in an ordinary installation.

Another useful set of apparatus is that known as the Silvertown portable testing set, which is contained in two small wooden boxes, one holding the batteries which are employed for the test, and the other the galvanometer, resistance coils, key, and com-

mutator. The apparatus is designed for facilitating tests of the resistance of the conductor itself, as well as of the insulating materials. Two separate batteries are employed—one of them consists of four low-resistance Leclanché cells, and is used for testing the conductor resistance; the other battery consists of thirty small Leclanché cells, which are divided into three equal sections, so that an electro-motive force of 15, 30, or 45 volts can be

FIG. 94.



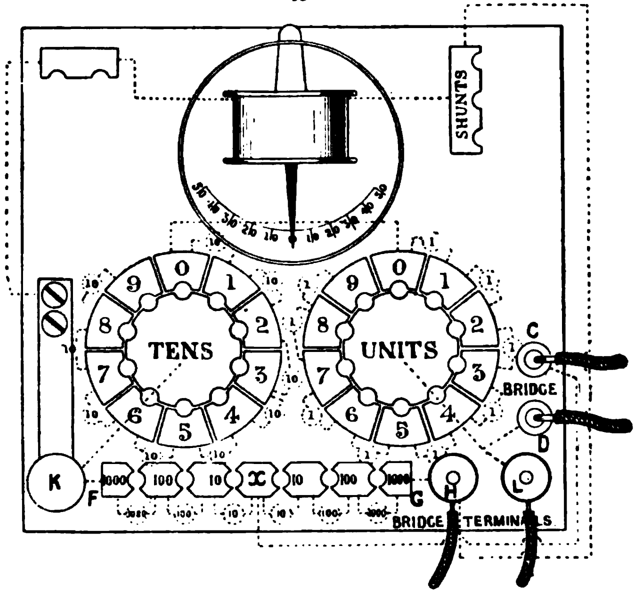
employed as occasion requires. The batteries are connected with the other apparatus by means of wires terminating in brass plugs, which are provided with ebonite handles, and which fit into circular plug-holes on the top of the box containing the measuring apparatus. This box, of which a plan is given in fig. 94, contains a sensitive horizontal galvanometer, the coil of which consists of many turns of fine wire. The needle is delicately mounted on a pivot, and carries a long but light aluminium pointer, which protrudes beyond the coil and travels over a scale.

The pivot is carried by a small slide, by means of which the needle can be withdrawn from the instrument for examination or repair. The needle is so magnetised that when the pointer is swinging freely and comes to rest in the zero position, the north-seeking pole of the needle is then pointing to the left-hand side of the box. Mounted in a recess on this side is a controlling magnet, the upper end of which, when in the vertical position, is nearer to the needle than the lower end. From what was said when describing the tangent galvanometer, it will be gathered that when the controlling magnet is placed with its north-seeking pole upwards, it is acting in antagonism to the earth's field, and by thus reducing the value of the controlling force the sensitiveness of the instrument is increased and a feebler current is required to produce any given deflection. When the magnet is reversed the controlling force is augmented—that is to say, the lines of force due to the magnet act in conjunction with those due to earth, and the sensitiveness of the instrument is reduced. The difference between the maximum and minimum values as affected by the positions of the controlling magnet is about 40 per cent. Insulation-resistance tests are usually effected with the galvanometer in its most sensitive condition, while the resistance of conductors is usually tested with the controlling magnet in the position for least sensitiveness, that is, with its south-seeking pole upwards. The controlling magnet is also of service in adjusting the needle to zero. In preparing to test, the box should be placed on a fairly level surface, with the left side towards the north, and the controlling magnet in a vertical position. The needle will then swing at or about its zero position, to which it can be brought exactly by a slight inclination of the controlling magnet to one side or the other. The dotted lines in the illustration (fig. 94) indicate the whole of the permanent electrical connections made inside the box.

In order to measure a low resistance, such as that of an electric light conductor, the connections are such as to convert the apparatus into a Wheatstone bridge, and to facilitate the tracing of these connections a separate diagram (fig. 95) is furnished, embracing only those parts of the apparatus required for this particular test. The poles of the battery are joined to the ter-

minals C and D respectively. From C the current travels to the block *x*, where it divides between the two arms of the bridge, each of which contains three coils of 10^{ω}, 100^{ω}, and $1,000^{\omega}$, as in the Post Office bridge (fig. 87). It will be remembered that at least one of the coils should be used in each of the arms. From the block F the current passes to another bridge-arm, consisting of a couple of rheostats, one comprising 9 coils each of 1^{ω} resistance,

FIG. 95.



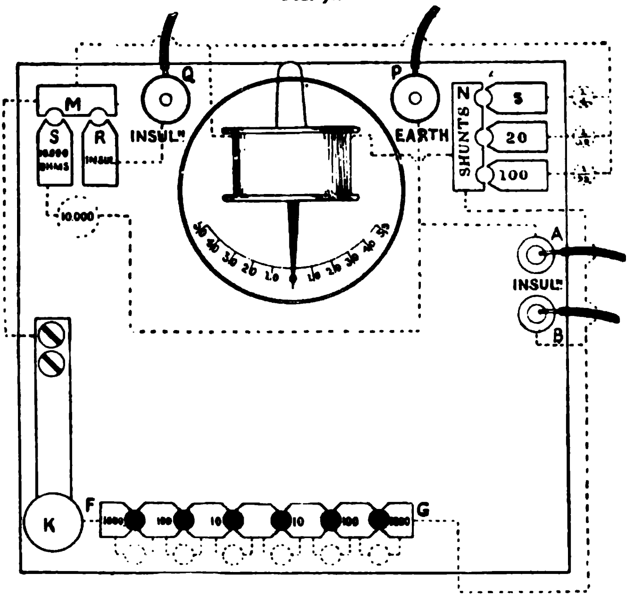
and the other 9 coils each of 10^{ω} resistance, so that the range of this arm is from 1^{ω} to 99^{ω}. The connections for these rheostats are similar to those in the form of bridge illustrated in fig. 90. It will be seen that the centre plate of the 'tens' rheostat is connected to the block F, and that the centre plate of the 'units' rheostat is connected to the terminal D (to which we have already connected one pole of the battery). The two zero or o blocks of the rheostats are connected together, and the coils are joined between the other blocks as shown in the figure, so that if, say, the

'tens' plug is placed in the block numbered '7,' and the 'units' plug in the block numbered '4,' the total resistance of the arm would be 74^{ω}.

To complete the other side of the bridge, block G is connected to the terminal H, and between this and terminal L is joined the conductor whose resistance has to be ascertained.

Between the blocks F and G the galvanometer must be connected, the path for which through the key, K, is shown by the

FIG. 96.



dotted lines. Theoretically the range of the bridge as illustrated in fig. 95 is from $0{\cdot}01^{\omega}$ to 9900^{ω}, but practically it is more restricted than this, the working range of the instrument being from 1^{ω} to 1000^{ω}. Outside these limits an increase of battery power is necessary in order to obtain satisfactory results.

Fig. 96 shows the positions of the apparatus employed and the connections involved for testing insulation resistance. One pole of the battery of, say, 30 cells is joined to terminal A, which

is joined direct to earth by way of terminal P. The other pole of the battery is joined to terminal B, which is connected to the 'shunt' block N, from which the current passes direct to the galvanometer and thence to another block, M. A plug is employed to continue the path to the block S, and thence through a resistance of 10,000$^\omega$ to the pole of the battery connected to terminal A. The galvanometer however, being somewhat sensitive, gets too much current when the resistance in circuit with the full battery is only 10,000$^\omega$, and it will be observed that between the shunt block N and the block M there are three shunt paths having reducing powers of 5, 20, and 100 respectively. If we suppose the highest shunt to be employed, then the galvanometer reading should be multiplied by 100, or, what amounts to the same thing, if the galvanometer with the one-hundredth shunt gives with the 10,000$^\omega$ coil in circuit a deflection of, say, 25 divisions, then the same deflection would be obtained were the unshunted galvanometer placed in circuit with a resistance of $10,000 \times 100 = 1,000,000^\omega$. But if the battery can produce a deflection of 25 divisions through 1 megohm, it will give one division through 25 megohms, and this latter resistance is the 'constant' of the instrument under these particular conditions. This constant we consider a better and simpler one to employ than that usually adopted, although of course the ultimate results are the same. We repeat, then, that the constant which we adopt is the value of that resistance through which the battery employed can produce a deflection of one division on the unshunted galvanometer. Having determined the constant, we are now in a position to make an insulation test. Let the plug be removed from the hole between M and S, and now placed in the hole between M and R. The current will then pass to terminal Q and thence into the conductor of the cable under test, one end of the conductor being joined to Q, the distant end being of course carefully insulated. Should the unshunted galvanometer now give a deflection of 25 divisions, the resistance of the insulating material is clearly one megohm. One or other of the shunt coils can, if necessary, be used in this test as well as in the preliminary test for the constant, and the reading of the galvanometer should then be

multiplied accordingly in order to obtain the theoretical deflection which the unshunted galvanometer would give. Suppose, for example, that the insulation resistance is so low that when the twentieth shunt is employed by inserting the plug, the reading obtained is $12\frac{1}{2}$ divisions, then the deflection on the unshunted galvanometer would be $12\frac{1}{2} \times 20 = 250$ divisions. But one division corresponds to 25 megohms, therefore 250 divisions would indicate a resistance of $\frac{25,000,000}{250} = 100,000$ ohms. In fact, to obtain the value of any resistance it is sufficient to divide the 'constant' by the deflection which would be obtained through that resistance on the unshunted galvanometer.

The key, K, can, with the holes in the blocks from F to G plugged up, be employed as a means for short-circuiting the galvanometer. This is frequently a great convenience, as its use facilitates the reading of the instrument by checking the oscillations of the needle.

CHAPTER VI.

MEASUREMENT OF ELECTRO-MOTIVE FORCE

In all classes of electrical work it is important to be able to accurately measure potential difference, or electro-motive force, and no better introduction to this branch of the subject can be obtained than that furnished by the study of the methods by which the electro-motive force of batteries can be compared. By Ohm's law we know that $E = C R$, where R is the total resistance of any circuit measured in ohms, C the current in amperes flowing through it, and E the electro-motive force in volts which maintains that current. So that, whenever the resistance and the current strength are known, the E.M.F. can be ascertained by multiplying these two quantities together. For instance, if a battery having a resistance of 15 ohms is joined up to send a current through a galvanometer of 320 ohms resistance, with a rheostat having 960 ohms unplugged, also in circuit, and if the resulting current is found to be 8 milliamperes, then the electro motive force of that battery is $C \times R$ or $\cdot 008 \times 1295 = 10 \cdot 36$ volts.

The measurement of current strength presents but little difficulty, but it is not often that the total resistance in the circuit is accurately known without measurement, and thus two tests at least are rendered necessary in order to ascertain the E.M.F. by this method. In practice it is usual to take some good constant cell or battery whose E.M.F. is known exactly and compare the unknown electro-motive forces with that of this 'Standard' cell or battery. The accuracy of the results depends, of course, upon the accuracy of the value which is given to the E.M.F. of this standard, and upon its constancy.

The best cell for a standard is that devised by Latimer Clark, and described in Chapter III. If carefully used it will remain constant for years; but, as it polarises quickly, it should not be

allowed to send so strong a current as even one milliampere, and, if possible, should only be used in those tests, to be presently described, in which the batteries are tested when they are not sending any current at all, but simply maintaining a potential difference. A rather serious drawback to this cell is, that its E.M.F. varies with a change of temperature, falling as the temperature rises; and although, the temperature being known, the variation of E.M.F. can be allowed for, such calculations are inconvenient and take time. Its E.M.F. at 15° Centigrade is 1·435 volt.

The Daniell cell when in good condition does not polarise, even when developing a strong current, and it has the further advantage that a considerable variation of temperature makes little or no difference in its E.M.F. It is, therefore, a good standard for use in the workshop, and any form of Daniell cell in first-rate order may be employed, especially when the tests are independent of the battery resistance. But it must be remembered that the plates should be bright and clean, the supply of crystals in the copper cell plentiful, and the solution in the zinc cell half saturated. The E.M.F. then is 1·079 volt.

Since the current which a battery can develop is proportional to its E.M.F., it is evident that the E.M.F. of two batteries can be compared by observing the currents which they send through circuits offering *equal* resistances. The Daniell cell should be used as the standard in this case, and if it gives on a tangent galvanometer 25 divisions deflection through a total resistance of, say, 1,000$^{\omega}$, while another cell or battery gives 62·5 divisions through the same resistance, then

$$25 : 62{\cdot}5 :: E : x,$$

where E is the E.M.F. of the standard cell, and x that of the battery under measurement.

Therefore $$x = \frac{62{\cdot}5 \times 1{\cdot}079}{25} = 2{\cdot}7 \text{ volts nearly.}$$

One objection to this method, when the external resistance is low, is, that it is necessary to know the resistance of the batteries, in order that the total resistance may be made the same in both

cases; but if the resistance of the external circuit is comparatively high, then the resistance of the batteries may be ignored.

In this simple method, the external resistance is kept constant, while the current varies. The different currents are then measured and the relative E.M.F. deduced therefrom directly, as the E.M.F. varies directly as the current produced.

But it is also possible to compare electro-motive forces by varying the resistance and keeping the current constant, in which case the electro-motive force is proportional to the resistance; for, the higher the E.M.F., the greater is the resistance through which it can send a given current. One great advantage in connection with this method is, that any kind of galvanometer which may be available can be employed, because the same deflection is produced in every case. In order to compare the E.M.F. of any battery x, with the standard cell E, we should in this method join up the standard cell in circuit with a rheostat and galvanometer, varying the resistance so as to obtain a convenient deflection of, say, 45°, and noting carefully the total resistance, R_1, in circuit. The battery to be tested should next be joined up, and the resistance altered, say, to R_2, so as to reproduce the deflection of 45°.

Then $$x : E :: R_2 : R_1, \text{ or } x = \frac{E\,R_2}{R_1}.$$

In this test, too, the resistances of the standard cell, the battery, and the galvanometer must be known and taken into account unless the resistance in the rheostat is comparatively high, when these other resistances may be ignored.

But by a simple extension of this method, it is possible to obtain an accurate result without knowing either of these three resistances. The process consists in first joining up the standard cell, E, in the same manner as in the previous test, and then adjusting the rheostat until a deflection of, say, 45° is obtained. The resistance should then be increased until the deflection falls to, say, 35°, noting carefully the exact number of ohms, P, by which the resistance is increased, in order to bring about the reduction in the deflection. The battery, whose electro-motive force, x, it is desired to measure, must now be substituted for the standard cell, and the resistance again adjusted until the deflection

of 45° is reproduced. This resistance should then be increased by, say, Q ohms until the deflection is once more 35°. Then, as shown below,

$$x : \text{E} :: \text{Q} : \text{P}, \text{ or } x = \text{E}\frac{\text{Q}}{\text{P}} \text{ volts.}$$

To take an example. If with the Daniell cell as a standard the insertion of 720 ohms reduces the deflection 10°, that is to say, from 45° to 35°, and when the battery whose E.M.F. is to be measured is substituted it is found necessary to add 2,300 ohms to reduce the deflection through the same 10°, then

$$x = 1{\cdot}076 \times \frac{2300}{720} = 3{\cdot}446 \text{ volts nearly.}$$

This is a very good method, and it is interesting and instructive to observe how the battery and galvanometer resistances are eliminated. This may be shown by Ohm's law as follows :—

Let G be the resistance of the galvanometer, r_1 the internal resistance of the standard cell, and R_1 the resistance in the rheostat when the needle is deflected through 45° by the current whose strength is indicated by C_1, then

$$\text{C}_1 = \frac{\text{E}}{\text{R}_1 + r_1 + \text{G}}.$$

Also let r_2 be the resistance of the battery whose E.M.F. is to be deduced, and R_2 the resistance in the rheostat necessary to reproduce the deflection of 45°, or when the current strength can again be indicated by C_1, then

$$\text{C}_1 = \frac{x}{\text{R}_2 + r_2 + \text{G}},$$

therefore
$$\frac{\text{E}}{\text{R}_1 + r_1 + \text{G}} = \frac{x}{\text{R}_2 + r_2 + \text{G}}$$

or
$$\text{E}(\text{R}_2 + r_2 + \text{G}) = x(\text{R}_1 + r_1 + \text{G}) \quad . \quad . \quad . \quad . \quad (1)$$

When the resistances R_1 and R_2 are increased by P and Q respectively to obtain the deflection of 35° which will correspond to a current strength which can be called C_2, then

$$\text{C}_2 = \frac{\text{E}}{\text{R}_1 + r_1 + \text{G} + \text{P}} = \frac{x}{\text{R}_2 + r_2 + \text{G} + \text{Q}},$$

therefore $$\text{E}(\text{R}_2 + r_2 + \text{G}) + \text{E}\,\text{Q} = x(\text{R}_1 + r_1 + \text{G}) + x\text{P} \quad . \quad (2).$$

Subtracting equation (1) from (2) we get

$$E\,Q = x\,P,$$

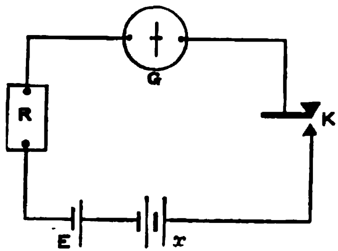
therefore

$$x = E\,\frac{Q}{P}.$$

To ensure accurate results it is essential that the galvanometer for this test should be sufficiently sensitive to indicate a very slight alteration in the current strength, and, if possible, the resistances P and Q should be as high as or even higher than the total resistance in the circuit prior to their insertion.

There is another good method which is sometimes very convenient because it is not necessary to know or ascertain the actual resistance of any portion of the apparatus, whether it be the galvanometer, the rheostat, or the battery. As in the previous tests, we may denote the E.M.F. of the standard cell by E, and that of the battery to be measured by x. The standard cell E and battery x are joined up in series, so that they assist each other in sending a current through a rheostat or set of resistance coils, R, and a tangent galvanometer, G (fig. 97), and the resistance adjusted until a fairly high deflection, say, sixty-five tangent divisions, is obtained. Then, on reversing the standard cell (supposing it to be of lower E.M.F. than x) so that the two E.M.F.'s, x and E, are opposed to each other, the resulting current will manifestly be due to the *difference* between the two E.M.F.'s, and, as the total resistance remains unaltered, the current and the deflection produced by it will be diminished, say, to twenty-five divisions. Then, denoting the first deflection (sixty-five divisions) due to both E.M.F.'s by D, and the second deflection (twenty-five divisions), due to the *difference* between the two E.M.F.'s when opposed, by d,

Fig. 97.



$$x : E :: D + d : D - d,$$

or

$$x = E\,\frac{D + d}{D - d}.$$

Inserting the values as above, we get

$$x = 1{\cdot}079 \times \frac{65 + 25}{65 - 25} = 2{\cdot}428 \text{ volts nearly.}$$

The object of reversing the battery or cell of lower E.M.F. is to obtain both deflections on the same side of the zero point. Were the battery of higher E.M.F. to be reversed, it would cause the needle to be deflected to the opposite side of the zero, and if the pointer happened to be bent an incorrect result would be obtained.

If, when joined up in opposition, no deflection is obtained, then the electro-motive force of the standard cell will be the same as that of the battery under test, or $E = x$. The only objection to the method is that in the first case the weaker battery, which is usually the standard cell, has a rather strong current flowing through it which may lower its E.M.F., while, when joined in opposition, the current is passing in the opposite direction and will almost certainly cause a slight increase in its E.M.F. In order to eliminate as much as possible this source of error, it is advisable to introduce a 'key' or contact-maker to open and close the circuit at will, as shown in fig. 97. By the skilful manipulation of this key the needle can be brought to rest immediately without a single oscillation, and the deflection then read before any appreciable alteration of the E.M.F. can take place. As a further precaution, the resistance in circuit should be made as high as possible so as to reduce the strength of the current. By such means the objection becomes almost entirely obviated. To admit of high resistance being placed in the circuit, the 320^{ω} coil of the galvanometer should be used unshunted, and the magnet placed rather low down with its north pole pointing northwards, so that it will act in opposition to the earth's magnetism.

That the resistance of the batteries and galvanometer need not be known or ascertained is evident from the fact that they form part of the constant total resistance, which is the same in each case and which need not enter into the calculation. This may be shown algebraically, for if we let R indicate the total resistance in circuit (including batteries and galvanometer), C_1 the current in the first

case giving deflection D, and C_2 the weaker current, giving deflection d, then

$$C_1 = \frac{x + E}{R}, \text{ or } R = \frac{x + E}{C_1},$$

and

$$C_2 = \frac{x - E}{R}, \text{ or } R = \frac{x - E}{C_2}.$$

Therefore $\frac{x + E}{C_1} = \frac{x - E}{C_2}$, or, since the currents are proportional to the deflections in tangent divisions, $\frac{x + E}{D} = \frac{x - E}{d}$.

Whence

$$D\,x - D\,E = d\,x + d\,E,$$
$$x(D - d) = E(D + d),$$
$$x = E\,\frac{D + d}{D - d}$$

It will doubtless be remembered that, if the poles of a battery are joined by a short piece of thick wire having practically no resistance, the current flowing through the circuit will depend simply upon the E.M.F. of the battery and its internal resistance. Now, the thick-wire coils of the tangent galvanometer which we have described are of very low resistance, and may be used for the measurement of the current which a battery can give under these conditions. Thus, supposing a battery of twenty Daniell cells, having a resistance of 5 ohms per cell, were joined up to send a current through one of the low resistance coils of the tangent galvanometer, the current flowing would be $\frac{20 \times 1{\cdot}079}{20 \times 5} = {\cdot}2158$ of an ampere, and the current from one cell, or 100 similar cells, should be the same, because when the E.M.F. is increased by increasing the number of cells, the internal resistance—that is, the total resistance in circuit—is increased in the same proportion. A galvanometer with a very low resistance coil affords, therefore, a means of rapidly testing the *condition* of a number of similar batteries, for the deflection of the needle will be decreased if either the internal resistance of any cell is above, or the E.M.F. of any cell below the standard. It is, then, only necessary to ascertain the deflection given by a cell or a battery known to be in good condition, and adopt this as the standard. Then if a battery, say,

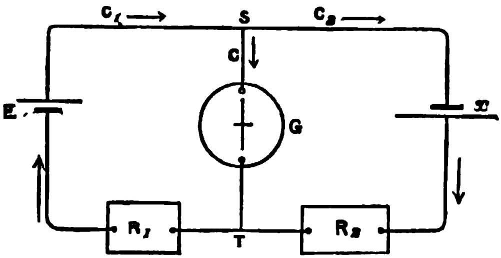
of ten cells gives a current equal to that of the standard cell, it may be fairly concluded that the battery is in good condition, but if a second similar battery gives a deflection of seven or eight degrees less, then the conclusion is that there is something wrong with it; its resistance is too high or its E.M.F. too low. The matter may be quickly decided by joining up the faulty battery in opposition with the similar battery known to be good—that is to say, joining their copper or positive poles together and their zinc or negative poles to the galvanometer. If they then give no deflection, we know that their electro-motive forces are equal, and the fault is proved to be one of high resistance. If, on the other hand, a current is produced, there must be a difference in E.M.F., and the fact that the suspected battery is the faulty one would be demonstrated if the direction of deflection were such as to prove that the other is urging a current through it.

But galvanometers with short thick wire coils having but a few convolutions are only affected by very powerful currents, and are only used where it is essential that the introduction of the instrument into any circuit should have no appreciable effect upon the strength of the current flowing through it. When this restriction is not imposed increased accuracy can usually be obtained by employing a more delicate instrument, in which a coil of many turns, and generally of fine wire offering a high resistance, is employed; because, although the current through the galvanometer is weakened by the added resistance, the effect is more than balanced by the increased number of times which the current travels round the needle. In fact, the flow of a very feeble current through such an instrument, or the maintenance of a very low difference of potential at its terminals, may suffice to produce a good deflection, while under similar conditions a galvanometer with a thick wire coil would be unaffected. It was observed, when considering the Wheatstone bridge method of measuring resistances (Chapter V.), that one great advantage pertaining to it is, that in making the final adjustment only a very weak current or no current at all passes through the galvanometer. It is therefore practicable in such cases to use a very delicate instrument, and, in order to prevent damage being done to the needle or its pivot, or to prevent the coils being fused by the passage of a heavy current,

the coil can be shunted until the adjustments are almost completed.

It will also be remembered that the instrument need not be of any particular design, since the final result is obtained with the needle undeflected; a galvanometer such as this can also be employed in several methods which have been devised for the comparison of electro-motive forces, in which the instrument is simply used to denote the *absence* of a current, and in which, therefore, the consequent advantages are the same as in the case

FIG. 98.



of the Wheatstone bridge. Fig. 98 shows the connections for one such method.

E is the standard cell, and x the battery whose E.M.F. is to be measured. R_1 R_2 are two sets of resistance coils, and G is a delicate galvanometer. A certain resistance is introduced into the circuit by unplugging the necessary coils in R_1, and the resistance in R_2 is adjusted until the current ceases to pass through the galvanometer, thus showing that the two points, S and T, have been brought to the same potential. This being the case, then

$$x : E :: R_2 : R_1,$$

therefore
$$x = E\frac{R_2}{R_1}.$$

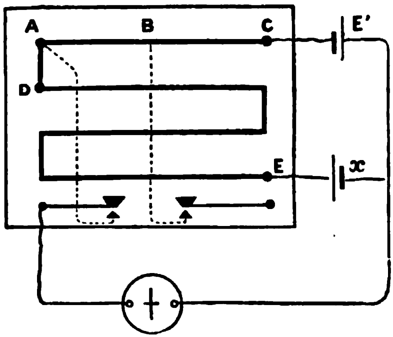
As an example, suppose the Daniell cell to be used as a standard, and R_1 fixed at 1,000 ohms, while the potentials at S and T are equalised by making R_2 5,650 ohms, then

$$x = 1 \cdot 079 \times \frac{5650}{1000} = 1 \cdot 079 \times 5 \cdot 65 = 6 \cdot 096 \text{ volts.}$$

It will be observed that the working out of this example is simplified on account of R_1 being made 1,000 ohms. For this reason it is preferable to always make the resistance in the same arm as the standard cell some multiple of 10, and obtain a balance by adjusting the other set of coils.

The horizontal galvanometer designed for use with the Wheatstone bridge answers very well for this test, and, as will be seen from fig. 99, the bridge itself may be used for the two sets of coils and then the usual key can be employed in the galvanometer circuit, while the 'infinity' plug between A and D can be used to break the battery circuit and so minimise any error due to polarisation.

FIG. 99.



When a delicate galvanometer is not available, R_1 and R_2 must be lower, but then the battery resistances become important and cannot be ignored. They may, however, be eliminated by increasing one of the resistances, say R_1, by a certain amount, say P ohms, and obtaining a balance again by increasing R_2 by Q ohms.

Then $$x : E :: Q : P,$$

therefore $$x = E\frac{Q}{P}.$$

The electro-motive forces are, in fact, simply proportional to the increase of the original resistances R_1 and R_2.

For example, if after one balance had been obtained, we were to increase the resistance R_1 by 500 ohms, and again obtain a balance by adding 2,852 ohms to R_2; then $P = 500$ and $Q = 2852$, therefore

$$x = 1{\cdot}079 \times \frac{2852}{500} = 6{\cdot}155 \text{ volts.}$$

The proof of the method depends upon two laws demonstrated by Kirchhoff, which we will endeavour to explain.

Let the resistance R_1 (fig. 98) be slightly reduced, so that the balance is upset, then the currents in the three arms will flow in the direction indicated by the arrows.

The first of Kirchhoff's laws (which is almost self-evident in the present simple case) states that the current flowing to the point S is equal to the sum of the currents flowing from it, that is,

$$C_1 = C_2 + C \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1).$$

The second law declares that in any complete circuit, even when it forms part of a network, as $R_1 E S T$, the sum of the products of the current strength in each arm into the resistance of that arm is equal to the sum of all the electro-motive forces in the circuit. That is to say, if in each arm or portion of the circuit the individual resistance of that arm is multiplied by the strength of the current flowing through that resistance, and if all the products so obtained are added together, then the sum so produced will be exactly equal to the sum obtained by adding together all the electro-motive forces in the various arms of the circuit.

The *algebraical* sum must, of course, be taken; for instance, if two currents, or two E.M.F.'s, are opposite in direction, one must be reckoned as *plus* and the other as *minus*.

In the circuit $R_1 E S T$ the only E.M.F. is that of the standard cell, which we denote by E, and, neglecting the internal resistance of this cell, we form the second equation thus:

$$E = C_1 R_1 + C G \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

G being the resistance of the galvanometer.

Similarly, in the circuit $R_2 x S T$, the only E.M.F. is x, but the currents in the two arms are in opposite directions. Therefore

$$x = C_2 R_2 - C G \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3).$$

By inserting in (2) the value of C_1, given in (1), we get

$$E = (C_2 + C) R_1 + C G,$$

that is, $$E = C_2 R_1 + C R_1 + C G \quad . \quad . \quad . \quad . \quad . \quad . \quad (4).$$

From (3), $$C_2 = \frac{C G + x}{R_2};$$

and, inserting this value for C_2 in (4), we get

$$E = \frac{R_1 (CG + x)}{R_2} + CR_1 + CG;$$

$$R_2 E = CR_1 G + R_1 x + CR_1 R_2 + CGR_2;$$

therefore
$$C = \frac{R_2 E - R_1 x}{R_1 G + R_1 R_2 + R_2 G} \quad . \quad . \quad . \quad . \quad . \quad . \quad (5).$$

This equation gives us the value of the current flowing in the galvanometer circuit when the balance is upset, in terms of the various electro-motive forces and resistances. But in making the test we adjust so that no current flows through the galvanometer; therefore, when a balance has been obtained, $C = 0$, and, consequently, the fraction which forms the right-hand side of equation (5) is equal to 0.

Therefore, the numerator of the fraction

$$R_2 E - R_1 x = 0,$$

that is,
$$R_2 E = R_1 x, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6).$$

and
$$x = E \frac{R_2}{R_1},$$

which proves the case when the battery resistances are so small as to be negligible.

Equation (6) holds good, in fact, so long as R_1 and R_2 represent the total resistance in their respective arms of the system.

When the resistances of the batteries cannot be ignored, they must be added to R_1 and R_2 respectively to make up the total resistance in the arm, and then equation (6) becomes

$$E (R_2 + r_2) = x (R_1 + r_1) \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where r_1 is the resistance of the standard cell, and r_2 that of the battery under test. Also, when R_1 is increased by P ohms, and R_2 by Q ohms,

$$E (R_2 + r_2 + Q) = x (R_1 + r_1 + P),$$

that is,
$$E (R_2 + r_2) + EQ = x (R_1 + r_1) + xP \quad . \quad . \quad . \quad (8).$$

Subtracting (7) from (8), we obtain

$$EQ = xP;$$

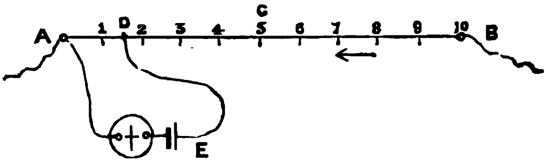
therefore
$$x = E \frac{Q}{P}.$$

There are a number of very beautiful methods for the comparison of electro-motive forces, somewhat similar in principle to those just described. We have selected a few and worked them out at length, not only because they are in themselves interesting, but also because they involve, in a rather simple form, some very important principles and laws which the student will do well to master.

We will now direct our attention to a method based upon a somewhat different principle. In this case, again, no current passes through the galvanometer when the final adjustment has been made, thus permitting the use of a delicate instrument. But a further very great point in its favour is the fact that the batteries do not send any current while their E.M.F.'s are being actually compared. Consequently, the Latimer Clark cell may be used as a standard to the best advantage, and the true E.M.F. of a battery subject to polarisation, like the Leclanché, can easily be measured; and further, since no current flows through the batteries or the galvanometer in the battery circuit, their resistances have no effect whatever, and therefore need not be known.

If between the ends A and B (fig. 100) of a uniform German-silver wire one metre (39·37 inches or 1,000 millimetres) in length,

FIG. 100.



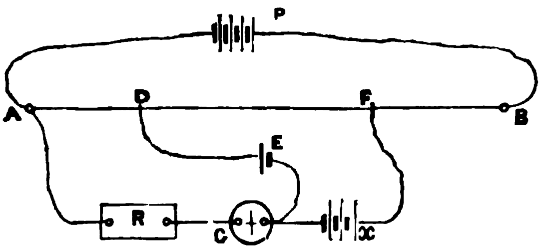
a potential difference of 10 volts is maintained, the fall of potential will be uniform, say, from B to A. Now it must be possible, under such conditions, to find a point in the wire such that the potential difference between that point and the end A shall be any desired fraction of 10 volts. For instance, between A and the middle of the wire, C, the difference is 5 volts. Furthermore, if the negative pole of the Clark standard cell E is joined to the point A, it will assume the same potential as that point, while the end of the wire connected to the positive pole will be 1·435 volt above that potential. A galvanometer may be joined up on either side of E

without affecting the final result, and if the free end of the wire is joined to any point near B a current will flow through the galvanometer G in opposition to the standard cell, because the potential of the point near B is more than 1·435 volt above that at A; while, on the other hand, if contact is made at a point very near to A, where the potential is less than 1·435 volt, the standard cell will be able to maintain a current through the galvanometer and deflect the needle in the direction opposite to that which resulted from making contact at the point near B. Now, between these two positions a point, D, may be found where the needle will be undeflected, showing that no current is passing in either direction through the standard cell and galvanometer, and this point will be such that the difference of potential between it and A is equal to the maximum difference of potential which the standard cell can produce, viz. its E.M.F. of 1·435 volt. Since each of the ten equal parts into which the wire is divided represents a potential difference of one volt, the point D, at which a balance is obtained with the standard cell, should be nearly midway between 1 and 2. If the wire is perfectly uniform in resistance, the fall of potential will also be perfectly uniform, and the exact position of the balancing-point would then be 143·5 millimetres from A. This shows the advantage of having a wire divided into 1,000 equal divisions. As another example, suppose the standard cell were replaced by a battery of unknown E.M.F., we could readily find its E.M.F. by making contact at different points along A B until the absence of a current through the galvanometer indicated that a point had been touched where the E.M.F. is balanced. If this point were 970 millimetres from A, then the E.M.F. of the battery would be 9·7 volts. We have remarked that the resistance of the galvanometer and battery may be high and yet not affect the final result. The only objection to high resistance is that when the balance is nearly, but not quite, obtained, the potential difference tending to send a current through the galvanometer is very small, and if the resistance in the galvanometer circuit is very high the resulting current will be weak and may not be able to affect the instrument. This would prevent the balancing-point being found exactly, and it is a good plan, in order to avoid such want of sensitiveness, to employ a very delicate galvanometer, and place a set of high

resistance coils in circuit with it. At first all the resistance should be unplugged; it can then be reduced as the adjustment becomes approximately correct, the final adjustment being made with all the resistance out of circuit. Injury to the galvanometer may thus be avoided, and the greatest possible degree of accuracy attained.

It is clear that if we could with certainty maintain a constant potential difference between the extremities of the graduated wire, no standard cell would be required, and it would be very convenient to be able to measure E.M.F.'s as simply proportional to a certain length of the wire. It is difficult, however, to maintain any given difference of potential between two points for any length of time, and therefore in practice a slightly different arrangement

FIG. 101.



to that just described is adopted. A current is sent through the wire A B (see fig. 101) from some fairly constant generator, P, such as a good low resistance battery or a few of the 'secondary cells' to be described hereafter, sufficient to maintain between A and B a potential difference greater than that of the highest E.M.F. to be measured. The wire is stretched over a scale divided into a thousand parts, and therefore, if of uniform gauge and material, the fall of potential along one of these units is equal to a thousandth part of the fall along the whole wire. The Clark cell, E, and the battery to be measured, x, are joined up with their negative poles connected through a galvanometer, G, and a set of coils, R, to the point A, as shown in fig. 101. Their other poles are connected to sliders, by means of which contact may be quickly made with any point along the wire. The whole of the resistance is put in circuit at first, and the slider connected to the standard battery is shifted

along until a point is found where the deflection on the galvanometer is very slight when contact is made with the wire A B. The resistance R is then gradually reduced until the exact point (D) is found. The distance from A to D must be carefully noted, and then a point, F, at which the E.M.F. of the battery x is balanced, is found in a similar manner. Now, the potential difference between A and D is equal to the E.M.F. of the standard cell—that is, 1·435 volt—and the potential difference between A and F is equal to the E.M.F. of the battery x. Therefore

$$\text{A D} : \text{A F} :: \text{E} : x.$$

Suppose A D to be 120, and A F 685, divisions; then

$$120 : 685 :: 1{\cdot}435 : x;$$

therefore $$x = \frac{685 \times 1{\cdot}435}{120} = 8{\cdot}19 \text{ volts.}$$

It will thus be seen that it is unnecessary to maintain any particular potential difference per unit of length of the wire, for this can be immediately found by means of the standard cell. But it is advisable, after the adjustments have been made as above, to verify the result by making contact with both sliders at almost the same moment, in order to ascertain whether or not the fall of potential has varied during the test.

In fact, one great feature in favour of this arrangement is that the test may so be made that a slight variation of the potential difference at the ends of the stretched wire need not cause any error; the source of inaccuracy which has most to be guarded against is a want of uniformity in the wire itself. By using a *low* resistance battery a greater proportion of the fall of potential takes place in the external circuit—that is, along the stretched wire—than when a high resistance battery is employed; hence the suitability of secondary cells for this purpose. A greater length of wire may be conveniently obtained by stretching it backwards and forwards several times upon a board. An instrument based upon the foregoing principles for measuring potential differences is commonly called a potentiometer. The wire is sometimes wound in a spiral groove round an ebonite cylinder, and, when made in

this form, it can easily be divided into 20,000 parts, but this type is rarely used for practical work.

In all the preceding methods potential difference is measured indirectly or by comparison. Instruments have, however, been devised which indicate directly, in volts, the difference of potential between any two points; such instruments are called voltmeters. That invented by Major Cardew is simple in principle, depending upon the elongation of a wire when heated by a current. If a wire is heated it increases in length. This linear expansion or extension is proportional to the product of the rise in temperature and the coefficient of expansion for the particular wire. The coefficient of linear expansion is defined as the elongation of a body of unit length when its temperature rises from zero to one degree (Centigrade), and this coefficient or proportional extension in the case of platinum, for example, is 0·0000088, so that, for an increase in temperature of 10° C., a yard of platinum wire would be extended to 1·000088 yard. By measuring the amount of extension produced by heating a wire, the increased temperature can therefore be inferred.

Now, when a current of electricity passes through a wire it performs a certain amount of work in overcoming its resistance, and the generation of heat is the result. The rise in temperature resulting from the generation of a certain amount of heat does not, however, bear a simple ratio to that amount of heat. It depends, in fact, upon the time or duration of the current and the specific heat or calorific capacity of the particular substance. The former of these factors is so very apparent that we need not further enlarge upon it. The specific heat of a body is defined as that quantity of heat which it absorbs when its temperature rises through a given range—say from zero to 1° C.—as compared with the quantity of heat which would be absorbed by an equal mass of water when its temperature is exalted through the same range. If, for example, a pound of mercury at 100° C. is mixed with, or placed in, a pound of water at zero, the temperature of the mixture will only be 3° C., so that, while the mercury has lost 97°, the equal mass of water has only increased 3°, or, in simple language, a quantity of water absorbs about thirty-two times as much heat as an equal weight of mercury, in undergoing the same exaltation

of temperature. The specific heat of water being taken as unity, that of mercury is therefore 0·03332. Similarly, the specific heat of platinum is 0·03244.

The variation in the temperature of a wire due to an increment or decrement of heat, depends also upon its weight or its sectional area, for it will be evident that if two wires of similar material and of equal resistance, but of different gauge or different weight—such, for example, as a given length of platinum wire weighing one gramme, and another platinum wire, twice as long, but weighing four grammes (offering, therefore, equal resistances)--have the same current passed through them, they will not be raised to the same temperature, although the amount of heat actually developed will be the same in each case. This follows from the fact that in the one case there is more material to heat than in the other.

When a current of electricity passes through a wire, and performs a certain amount of work in overcoming its resistance, the equivalent of the quantity of energy absorbed in the performance of this work is seen in the development of a definite amount of heat which is imparted to the wire. The heat (H) developed in a unit of time is, in fact, directly proportional to the amount of power expended in overcoming the resistance of the conductor—that is to say, it is proportional to the product of the difference of potential, E, between its extremities, into the strength of the current, C, which is maintained through it, or H varies as $E \times C$. If the resistance of the wire remains constant, the value of C varies directly as E; by doubling E, C is also doubled, and the heat developed then varies as the square of E.

Again, the heat unit is defined as that amount of heat which is required to raise 1 gramme of water through 1° C. in temperature, and a potential difference of 1 volt maintained through a resistance of 1 ohm develops 0·24 such heat units per second—that is to say, the number of heat units, H, developed in t seconds, is

$$H = 0{\cdot}24 \times E\,C\,t.$$

As $E = C\,R$, it follows that $E\,C = C^2\,R$, so that the formula may also be expressed by saying that

$$H = 0{\cdot}24 \times C^2\,R\,t.$$

Collecting all these facts into one simple formula, where T° represents the rise in temperature in Centigrade degrees, E the potential difference in volts, C the current strength in amperes, t the time in seconds, h the specific heat, g the weight of the metal in grammes, and 0·24 the constant which, as pointed out above, is necessary to obtain a result on the Centigrade scale, we may say that

$$T^\circ = 0{\cdot}24 \times \frac{E\,C\,t}{g\,h} = 0{\cdot}24 \times \frac{C^2\,R\,t}{g\,h};$$

so that a current of one ampere, flowing for one second through 1 gramme of water (whose specific heat is 1·0), and offering 1 ohm resistance, involving, therefore, a potential difference of 1 volt, would, if all the energy expended were devoted to the generation of heat, be raised 0·24° C. in temperature.

Similarly, if the same current were maintained through a platinum wire of the same weight and resistance, the increase of temperature would be

$$T^\circ = 0{\cdot}24 \times \frac{E\,C\,t}{g\,h} = 0{\cdot}24 \times \frac{1 \times 1 \times 1}{1 \times 0{\cdot}03244} = 0{\cdot}24 \times \frac{1}{0{\cdot}03244}$$

$$= 7{\cdot}4^\circ \text{ C., nearly.}$$

The coefficient of linear expansion for platinum being 0·0000088, it follows that with a wire 100 inches long the elongation produced by an increase in temperature from 0° C. to 7·4° C. would increase the length of the wire to

$$100 + (7{\cdot}4 \times 100 \times 0{\cdot}0000088) = 100{\cdot}006512 \text{ inches.}$$

In the Cardew voltmeter a length of very fine platinum-silver wire is employed, and is heated by the passage of the currents whose E.M.F. it is desired to test. In each test, therefore, g and h retain the same values, and by limiting the increase of temperature to a few degrees, the very slight variation of R becomes a negligible quantity. Similarly, by employing a fine wire, it speedily rises to such a tempetature that, with any given current, the loss of heat due to radiation equals in amount that which is developed by the current. The only really variable quantities, therefore, are E and C. But, as already pointed out, C varies uniformly with E, and if the facilities for radiation remain the same, the increase of temperature, and with it the elongation, will always be the same for

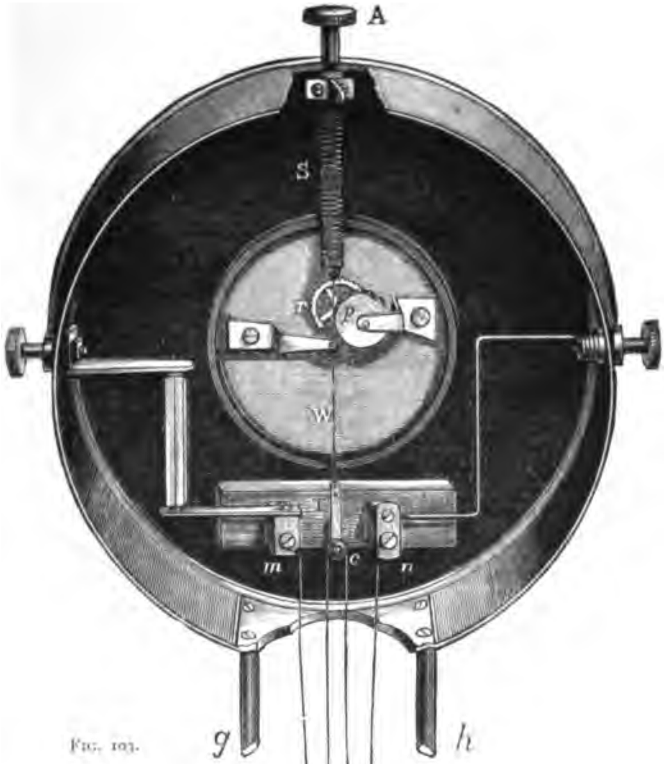
any given value of E. Hence, the amount of elongation can be made to indicate the potential difference maintained between the extremities of the wire.

Simple as the principle is, the construction of a reliable practical instrument is a matter of some difficulty, and an enormous amount of experimental work has been performed in determining the exact sources of error to which a Cardew voltmeter is liable. Fig. 102 illustrates the form of this instrument adopted by Messrs. Goolden after an exhaustive series of experiments extending over a number of years, and in it the inherent sources of variation and error are practically eliminated. The outer casing is removed to show the essential parts as viewed from the back.

The platinum-silver wire is 0·0025 inch ($2\frac{1}{2}$ mils) in diameter, and is fixed at one end to the small brass block *m*. Thence it is led round one of two grooved pulleys supported by a ring at the ends of two metal rods, *g h*, which are about 36 inches long, and are fixed to the brass base-plate. From this pulley the wire returns, and is passed round a small pulley, *c*; thence it is led to the second pulley at the top of the rods, and is finally terminated at the small brass block *n*. The brass pieces *m* and *n* are supported by the insulating block of varnished vulcanised fibre, which is securely fastened to the brass base-plate, and *m* and *n* are connected each to one of the main terminals of the instrument, which are insulated by ebonite or fibre collars from the brass casing. The wire should pass round the pulleys at the top of the rods in such a manner that a pull at *c* on the two centre wires would cause both pulleys to rotate in the same direction, and, the spindle being pivoted in jewelled holes, the friction is reduced to a minimum.

The small part, *c*, referred to as a pulley, only acts as such during the wiring of the instrument, as the extension of the wire when the apparatus is subsequently used does not cause it to rotate. It is made of vulcanised fibre, with a small groove round its circumference in which the wire lies, and is fixed by a small screw passing loosely through its centre to one end of the thin brass strip T, the other end of which has attached to it a fine platinum-silver wire, W, connected to the spiral spring S. The tension of this spring, which can be varied by means of the adjusting screw A, keeps the wires taut, and when the main terminals

FIG. 102.



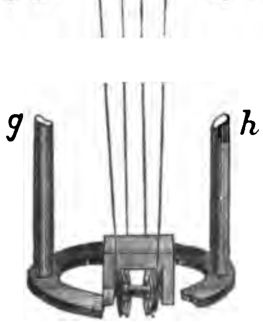


FIG. 103.

are connected to points in a circuit at different potentials, a current passes—say to the block *m*—up the wire, and round the first pulley back to the insulating reel, *c*; thence, again to the top of the instrument, round the second pulley, and back by way of *n* to the other terminal. This current heats the wire, which expands, and the slack is immediately taken up by the spiral spring S, so that the small brass strip T and the wire W are moved through a distance equal to the expansion of *two* lengths of the heated wire. The amount of expansion (and therefore of the potential difference applied) is measured by observing the distance through which the length of wire W is moved; but as this distance is, at the most, extremely small, some mechanical multiplying arrangement is necessary, and, since the force producing the movement is also very feeble, great care must be exercised in avoiding the introduction of any appreciable friction. These results are attained by the use of a jewelled watch movement. The wire W is led round a small pulley, *p*, fixed upon the same spindle as a toothed wheel, *r*, which gears into a small pinion, the spindle of which carries a long needle or pointer, passing over a scale-plate at the back of, and not visible in, the figure. When the wire is extended by the current, the spring S causes the pulley *p* to turn through a small angle, and with it also the wheel *r*, the pinion, and the pointer; and, as the diameter of the wheel is much greater than that of the pinion, the pointer is turned through a large angle by a comparatively small extension of the wire.

The passing of the wire W round the pulley so as to get a reliable grip, and at the same time avoid friction or risk of damage to the fine wire, is a more difficult matter than might at first sight appear. The pulley is shown separately in fig. 103. It has two narrow parallel grooves round its circumference, at one part of which (where it is filed away flat) two set-screws are fixed, both screwed up home. The wire is led from T round the first groove to the screw-heads, between which it passes over to the second groove, in which it completes its journey round the pulley, and is then led to the spiral spring.

The wire is so fine that it would not bear being pinched under the screw-heads, but the arrangement described effectually overcomes any tendency to slip; and as the pulley only moves through

a small angle, never making a complete revolution, no sensible friction is introduced. Insignificant as this detail may appear, it is, as already indicated, very important, and the same remark applies to the shape of the spiral spring S and to the material of which it is composed. The gradual alteration of this spring was found to be the main cause of the slight variation from zero which was frequently observed in the earlier instruments. It is necessary that the tension of this spring should remain constant; and the difficulty has been surmounted by (*a*) choosing a spring little liable to vary, spiral in form and of German silver, and (*b*) providing a thumbscrew A on the outside of the case, by turning which the pointer can, in the event of any variation, be readily restored to zero. Although there are four straight lengths of wire equally heated, it will be remembered that, since *c* does not rotate, the expansion measured is equal to only that of two lengths, for the movement would be the same as if one of the wires were rigidly fixed to it and the other removed. But it will be noticed that the tension due to the spiral spring is equally distributed between the two wires leading from *c*, and this affords the great advantage that double the tension can be given to the spring, which means that the force with which the pulley *p* is turned can be doubled, and any slight error due to friction correspondingly reduced, without, at the same time, necessitating the adoption of a comparatively thick wire. The wheel work is well made, but it is of course impossible to altogether avoid 'back lash'—that is to say, as the teeth of the driving-wheel do not fit tight between the teeth of the pinion, the latter does not begin to move absolutely at the same moment that the driving-wheel does when its motion is reversed. To avoid the slight error which this might cause, a hair-spring is fixed to the pinion spindle. This spring is visible in fig. 102, the pinion being immediately behind and therefore hidden by it. It is adjusted so as to maintain sufficient pressure between the teeth of the wheel and pinion to keep them always in contact, so that in either direction the two move simultaneously.

The whole of the casing is of brass, wood, from its liability to warp, being wholly unsuitable; but it is clear that the rods (*g h*, fig. 102) cannot be made of that metal, as, its coefficient of expansion being higher than that of platinum-silver, it would expand

more than the wire with any rise of temperature, atmospheric or otherwise, and cause a deflection of the pointer. On account of the expense, platinum-silver cannot be employed for these rods. Iron has, however, a lower coefficient of expansion than the wire, and the rods are therefore made partly of iron and partly of brass, the length of these parts being so proportioned that the greater expansion or contraction of the brass shall be neutralised by the lesser expansion or contraction of the iron, and the whole rod vary in length in exactly the same proportion as the wire itself. The wires are encased throughout their length by a brass tube which can easily be removed, and the arrangement of the pulleys, together with an opening in the supporting ring to which they are attached, facilitates the re-wiring of the instrument. In order to prevent damage to the working wire by the accidental passage of a too powerful current, a safety fuse is inserted in series with it, consisting of a short length of platinum-silver wire, 0·0014 inch ($1\frac{2}{5}$ mils) in diameter, which fuses and breaks the circuit before the current attains sufficient strength to fuse the thicker working wire. This fuse-wire is placed in a slit along the face of a rectangular strip of vulcanised fibre, each end being terminated at a round-headed brass screw in the end of the block, which is firmly held between two flat springs making contact with the screw-heads, one spring being connected to *m* and the other to the left-hand terminal. Connection between *n* and the other terminal is made by a stout, stiff wire.

This type of instrument, in which the wires are supported by the two compound rods, and in which the tube slipped over them simply acts as a casing to protect the wires from air currents and damage, is designed for use with the tube in a vertical position, the end at which the pulleys are fixed being placed uppermost. Now, as soon as the wire gets hot, it heats the adjacent air, which, being displaced by colder air, rises, and consequently currents are set circulating in the tube. The result is that when the pointer is deflected a slight oscillation may be observed, sufficient to prevent the value of the potential difference being read with certainty to within half a volt. This oscillation can be entirely eliminated by simply placing the tube in a horizontal position, for the whole length of the wire then lies in a more evenly heated atmosphere,

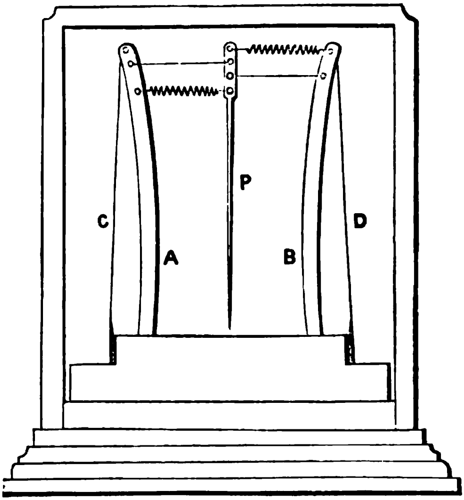
in which such air currents as rise from it are feebler and more uniform in their distribution in relation to the wire. When, however, the instrument is used horizontally, a further slight error is introduced in consequence of the increased friction.

A more accurate, though more expensive, instrument is made by dispensing with the rods and fixing the jewelled pulley bearings in the end of the tube itself, which, of course, is then compounded, being made of brass and iron in the necessary proportions. Such instruments are better adapted for experimental work, on account of their greater accuracy, and are, of course, always employed in the horizontal position. The rod pattern (which can also be used horizontally) is, however, a useful piece of apparatus for the engine-room or workshop, where a possible error of half a volt in the reading is a matter of little moment, and it has the advantage that the working wire can be more easily replaced than in the tube form. The voltmeter illustrated is capable of measuring from 30 to 120 volts. The calibration is carefully performed, the wire being continually heated by the passage of a current, and stretched, for some days previously, to bring it to its normal condition. As it is the heating of the wire which affords a measure of the electro-motive force, the 'heating-error' peculiar to most voltmeters is here entirely absent, and the instrument may be, and in fact is, kept continually connected up for days and weeks together. For the same reason, the reading is unaffected by the presence of external currents or any electro-magnetic field, and, as iron is not employed and the wire is not coiled, its self-induction is practically *nil.* Hence, alternating potential differences can be measured; but it must be remembered that this same absence of self-induction in the instrument, in allowing a current to rise suddenly to its full value, limits the range through which the fuse can protect the working wire; for, although the fuse acts with certainty if the current rises at all gradually, a very sudden application of a very high E.M.F. would develop a heavy current instantaneously, fuse and wire being melted simultaneously.

Although the instruments are made to register up to 120 volts only, the values of the readings can very easily be increased by inserting in the circuit, in series with the voltmeter, resistance

coils of various multiplying powers. Thus, if a coil equal in resistance to the wire in the voltmeter were introduced, it would exactly halve the potential difference of the current at the terminals of the voltmeter due to any particular E.M.F. Manifestly, such a coil would have a multiplying power of two, while a coil of three times the resistance would reduce the proportion of potential difference absorbed by the voltmeter to one-fourth, and therefore have a multiplying power of four. These resistance coils, however, must not be of the ordinary type. The wire should be of platinum-silver, of the same gauge as in the voltmeter, and in order to produce exactly equal facilities for radiation it should be bare, and, for convenience, it may be stretched in tubes similar to those employed in the voltmeter itself. In another form of resistance the wire is stretched over a rectangular framework made by attaching two rods of slate to a couple of strips of wood, notches being made in the slate to receive the wire and prevent one portion slipping into contact with another. The wire and framework are enclosed by pieces of thin sheet iron.

FIG. 104.



The ordinary Cardew voltmeter is not available for the estimation of low potential differences, owing to the exceedingly small elongation due to the slight rise in temperature, and the consequent vagueness of the reading which would result therefrom.

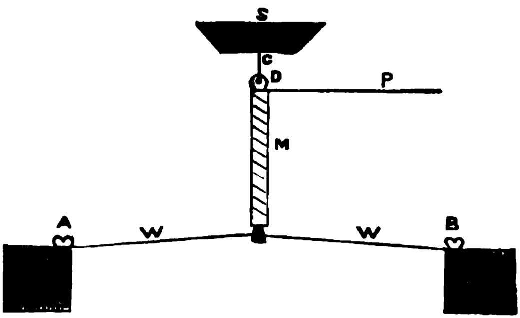
Recognising the necessity for the production of an instrument capable of measuring low E.M.F.'s—more particularly for testing the voltage of secondary cells—Major Cardew has designed one,

the working parts being shown in fig. 104. The range is from 0·5 to 2·5 volts, the scale being divided into tenths of a volt.

Two pieces of platinum-silver wire, C and D, are kept taut by means of the upright bows, A B. The indicating needle P is supported and held in position by two horizontal pieces of wire and a couple of spiral springs. The lower ends of the wires C D are connected to terminals on the case of the instrument, so that when a current passes through the instrument it travels up one wire and across, by way of the thicker part of the needle, to the other wire. This current raises the temperature of the wires C and D, which, by their consequent extension, allow the upper ends of the bows to approach each other. This motion is transmitted by means of the stiff horizontal wires to the needle, which therefore travels over the scale from right to left. In the figure the needle is shown over the centre of the scale as if deflected by the application of an E.M.F. of 1·33 volt. It will be observed that there is absolutely no friction—a most important feature, which, as a matter of fact, renders the instrument a possibility.

Professors Ayrton and Perry designed another, but somewhat more complicated, modification of the Cardew voltmeter, which is

FIG. 105.

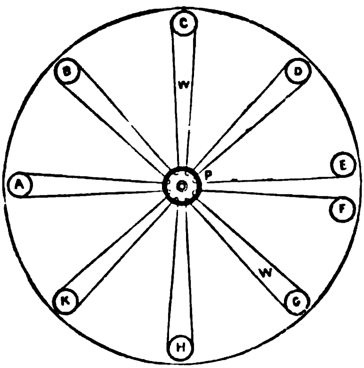


capable of accurately measuring low potential differences, and indicating small fractions of a volt. The instrument is not much used in practice, but the principle upon which it is constructed is instructive, and will be easily understood by a reference to the diagram, fig. 105. W W is a short piece of platinum-silver wire, 0·0014 inch in diameter. The ends of this wire are held rigidly

by the terminal screws A and B. The centre of the wire rests in a stirrup supported by the magnifying spring M, which is similar to that illustrated in fig. 63. The upper end of the spring carries a pointer, P, and is kept in position by a piece of fine wire, C D, fixed, at its upper extremity, to the support S. On a comparatively feeble current—that is to say, a current caused by a small difference of potential—passing through the wire W, it is elongated and the sag is increased. The tension on the spring is thereby reduced, and, the lower end being fixed, the upper end revolves and carries the pointer with it. The pointer moves over a dial, and indicates directly the amount of coiling to which the spring is subjected by the sag on the wire. So sensitive is this arrangement that when the initial sag on the wire is comparatively small—that is to say, when the wire is stretched almost in a straight line between the terminals—sufficient change in the sag results from the application of a potential difference of eight or ten volts at the extremities of a wire eight inches long to produce, when magnified by the spring, a complete rotation of the pointer.

If, in a voltmeter of this kind, the wire is further shortened, the instrument will indicate a still lower potential difference,

FIG. 106.



because the shortening decreases the resistance, and so augments the current resulting from a given potential difference, and also because, the mass of the wire being reduced, its temperature rises higher with a given quantity of heat. But the wire cannot be shortened indefinitely, as it is so fine that the temperature beyond which it is unsafe to work is quickly reached. It is, however, possible to obtain the first-mentioned effect without the second. For instance, in the case of what may be called the bicycle-wheel form of instrument (fig. 106), the whole of the wires corresponding to the spokes of the wheel can be joined in series, or grouped variously in

parallel. In the latter case, the resistance being much decreased, the stronger current develops a greater amount of heat, thus affording a means by which an instrument may be used for much lower potential differences than it can be with the spokes in series. The mass of metal affected by the heat is, however, the same in either case.

The design of this form of the instrument is ingenious. Round a ring of metal a number of non-conducting studs, A B C, &c., are fixed. There is also a small non-conducting central piece, P, to which a magnifying spring is attached, at right angles to the plane of the ring. One end of the wire is attached to the stud E, and passes to and fro between the hub or centre-piece P and the various studs, the other end being fixed to the stud F. This device has the advantage that every portion of the wire is affected by the current, so that there is no need to introduce resistance coils into the external circuit to indicate the higher voltages, all that is necessary being, as already indicated, to join the 'spokes' in series.

In some instruments of this class of hot-wire voltmeters, constructed to measure the alternating potential difference at the terminals of a coil used in electrical welding, the range is from 1 to 2 volts. The scale is 6 inches in diameter and divided into hundredths of a volt.

We come now to a consideration of the means adopted to convert the instruments which we described in Chapter IV. as available for the measurement of current strength, and which are called ammeters, so that they can be employed as voltmeters.

An ammeter measures directly the strength of the current flowing through its coils, and this current is proportional to the difference of potential at the terminals of the instrument. It might, therefore, at first sight appear that any ammeter could be used to measure the potential difference between any two points by simply joining it up to them, observing the strength of the current flowing, and from that inferring the difference of potential which maintains it. It is evident that to measure the potential difference between two points it is essential that the terminals of the instrument should be joined directly to those points. But the very act of connecting two points in a circuit by a low resist-

ance ammeter would alter the distribution of the potential difference considerably. Let us suppose, for example, that it is desired that an instrument of low resistance shall be used to measure the electro-motive force of a primary battery of appreciable internal resistance. Then the potential difference which is measured by joining the instrument to the terminals of the battery is not equal to the E.M.F. of the battery, but only to the fall of potential through the instrument. Again, if the battery is supplying current to any particular circuit, and it is desired to measure the potential difference at the terminals of that circuit, the measuring instrument would have to be joined across the terminals of the circuit, and would therefore form a shunt to it, and if the instrument had a low resistance it would manifestly reduce the strength of the current flowing through the circuit; or, in other words, the very act of joining up the instrument to measure the potential difference would lower that potential difference which it is desired to measure.

Consequently, although the ammeter so placed would correctly indicate the potential difference between the two points *after* they were so joined, it would give no information as to their condition before. For instance, if a piece of German-silver wire, having a resistance of 5 ohms, forms part of a circuit through which a current of 4 amperes is flowing, we know, since $E = C \times R$, that the difference of potential between its extremities is $4 \times 5 = 20$ volts. If we proceed to measure these volts, by connecting an ammeter having a fraction of an ohm resistance to the ends of the wire, we shall get much less than 20 volts, for the resistance, and therefore the fall of potential, in that portion of the circuit will have been considerably lowered. Although the total current in the main circuit will be increased by this lowering of the total resistance, the ammeter resistance is so low that it shunts the greater part of the current from the German-silver wire; and supposing that, in consequence, only half an ampere flows through that wire, the potential difference at its ends will be $C \times R = \cdot5 \times 5 = 2\cdot5$ volts only, instead of 20, and of course there would be this decreased potential difference at the terminals of, and indicated by, the ammeter.

In order that the introduction of the instrument should make

absolutely no alteration, no current at all should flow through it; and although there are instruments which satisfy this condition, many of them are only suitable for use in the laboratory. If, however, we take any ordinary ammeter, and wind it with a large number of turns of fine wire, so that it has a very high resistance, it can be used as a voltmeter; for its resistance will be too great, and the current which passes through it will be too small, to make any sensible alteration in the potential difference which it is measuring; while, on the other hand, the large number of turns of wire will allow the feeble current so flowing to produce a sufficiently strong magnetic field to actuate the movable part of the apparatus. For instance, one of the ammeters, described in Chapter IV., when wound with fine wire to a resistance of about 2,000 ohms, will serve to measure potential differences of from 60 to 120 volts. Of course, it can and must be calibrated for reading in volts, in the same way that the ammeter was calibrated for reading in amperes.

One important source of error must, however, be guarded against; it is due to the fact that a current, in passing through the coils of a voltmeter, heats the wire and increases its resistance, and consequently a given difference of potential will send a weaker current through the coils after they are heated than before. The instrument will therefore indicate a lower difference of potential than that which actually exists, in consequence of the fact that it measures the potential difference by the strength of the current set up by that difference. For this reason a wire which is thicker and therefore longer than would otherwise be necessary is used, and in many instances efforts are made to facilitate radiation and ventilation, and thereby to keep the temperature tolerably uniform. In fact no effort should be spared to prevent the coils of a voltmeter being heated to any appreciable extent by the current. The heating-errors may even be caused by the relatively high temperatures of many engine rooms. This arises from the fact that electro-magnetic voltmeters are wound with copper, which, it may be remembered (see p. 22), increases in resistance 0·29 per cent. per degree centigrade increase of temperature; and supposing the instrument to have been calibrated at a temperature of say 15° C., it is easy to imagine a state of affairs which would

cause an increase of 5 per cent. in the resistance of the instrument, and a correspondingly smaller current to flow through it, when a certain potential difference is applied at its terminals. Under such circumstances the instrument will indicate lower voltages than it should do. Some engineers get over the heating-error due to the current by having a small switch in circuit with the voltmeter, and only placing the instrument in circuit when it is desired to take a reading. This can, of course, be done by closing the circuit of the switch and taking the reading before the wire has had time to get hot. In the case of an ammeter the resistance of the coils is usually very low, and, the size of the wire being comparatively great, the temperature, and therefore the resistance, varies but slightly, except at or near the highest indication on the scale. Many ammeters get warm if the strongest currents for which they are constructed are maintained through them for any considerable time. An ammeter, however, is not used as a shunt, but is placed directly in the circuit, and it is virtually free from the 'heating-error,' because, under all circumstances, the strength of the current flowing through it and measured by it is the same as that in the rest of the circuit.

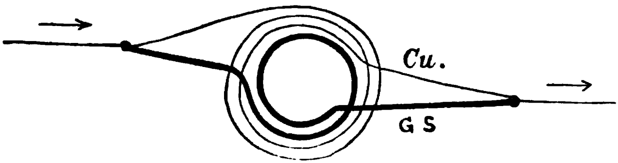
The Schuckert ammeter, and many others of a similar character which we have not described, can be converted into voltmeters by the simple substitution of a long-wire coil of high resistance for the short-wire coil of low resistance, and this, apart from the calibration, being the only essential difference between these types of instruments, there is no need to further enlarge upon them. An exception may perhaps be made in the case of Evershed's Gravity voltmeter, a general view of which is given in fig. 107. Its moving parts are exactly similar to those of the Gravity ammeter shown in fig. 67, but, of course, thin wire, offering high resistance, is employed. Only a portion of this wire forms the actual

FIG. 107.

magnetising coil, this being of copper, while the remainder, which is of German silver, is wound round a large metallic cylinder inside the casing. In an instrument indicating up to 110 volts the total resistance would be rather over 2,000 ohms, that of the actual magnetising coil being about 200 ohms, so that, with the maximum potential difference, the power absorbed is only 6 watts; and, as the temperature coefficient of German silver is low, and the disposition of the wire gives fairly good facilities for radiation, its resistance does not rise appreciably. Consequently, the instrument may be left continually on the circuit without causing any serious error under ordinary working conditions.

For cases where it is imperative that the indications should be entirely free from heating-error, Mr. Evershed has suggested a very ingenious method of compensating which may be applied to this

FIG. 108.



or any similar voltmeter. It is based upon the observed fact that the temperature coefficients of metals are different—that is to say, a given rise of temperature causes a greater increase per cent. in the resistance of some metals than of others, the difference in certain cases, such as copper and German silver, being considerable. The magnetising coil proper consists of German-silver wire, and a higher resistance coil of copper wire is wound round it in the reverse direction, as indicated in fig. 108, the two being connected in parallel, so that the copper coil not only forms a shunt to, but opposes the magnetic effect of the other coil, the resultant force acting on the needle being due to the excess of the magnetic effect of the German-silver over that of the copper coil. The wire of the latter is made very thin, to enable the necessary resistance to be obtained while keeping the ampere-turns sufficiently low, the number of ampere-turns in the German-silver coil being several

times greater than in the copper. When the current, or atmospheric changes, cause a rise in temperature, and therefore also in resistance, the current in the German-silver coil decreases slightly, but that in the copper coil decreases in a much faster ratio, because the temperature coefficient of copper is so much greater; and if the resistances and diameters of the two wires are made such that the current in the copper coil decreases just fast enough to keep the difference between the magnetic effects of the two coils constant, the instrument will compensate itself for any variation in temperature. Unfortunately, the calculations required are somewhat difficult, and the copper wire must be extremely thin, so that this ingenious method has not made much headway.

In describing the Evershed ammeter it was mentioned that a new pattern had been introduced, the difference consisting chiefly in that part of the instrument placed inside the coil, this portion now being identical for ammeters and voltmeters of all sizes, whether for direct or for alternating currents. Figs.

FIG. 109.

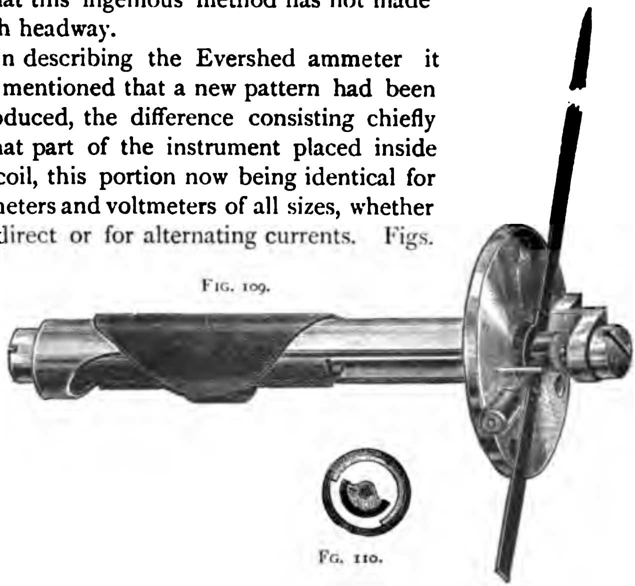


FIG. 110.

109 and 110 illustrate this important part of the new instruments. A horizontal brass spindle is pivoted in the ends of two set screws, one of which passes through the small brass angle piece fixed on the face of the disc, the other passing through the rear end of the brass tube, whose front end is also rigidly fixed to the brass disc. This brass tube is partly cut away through almost its entire

length, the object being to prevent the production of eddy currents in the tube when alternating currents pass through the coil, and the small curved iron 'needle' which is carried by the spindle can be seen through the opening.

A peculiarly shaped piece of sheet iron embraces the brass tube, to which it fits, friction-tight ; it is cut away, as shown on the side visible in fig. 109, but is continuous on the side which is hidden from view. The top of the pointer moves from left to right over the scale when deflected from zero, and it is shown as though deflected through about half its entire range. It will be seen that the inner curved piece, or 'needle,' is being rotated round into a position where it forms a more nearly complete cylinder with the outer iron sheet, and a stronger current would rotate it still further round, the maximum deflection possible being obtained when the magnetic circuit formed by the two pieces becomes as good as possible. A section at right angles to the spindle through the middle of the outer sleeve is given in fig. 110. This outer iron sleeve there shows as if it were a complete cylinder, broken only at the joint, but it will, of course, be gathered from the perspective view that nearer the ends of the sleeve its section would be only a part of a circle. The section also shows the manner in which the small semi-cylinder of iron is attached to the spindle.

The pointer is made of aluminium, and, as shown in fig. 109, it has a small weight attached to it to urge it towards zero, as in the older type of instrument. It moves in front of an engraved brass scale plate, which, when used for alternating work, is split from the hole through which the spindle passes, down to the circumference at the bottom of the plate, in order to prevent eddy currents being set up in the plate.

The heating error is reduced by the usual device of employing a comparatively small length of fairly thick copper wire for the working coil, and inserting in series with it a resistance coil, the wire of which is made from an alloy having a low temperature coefficient. The proportions are arranged so that the working coil gives from 400 to 500 ampere turns when the maximum pressure which the voltmeter can indicate is maintained between its terminals, and the total loss in the instrument is then about

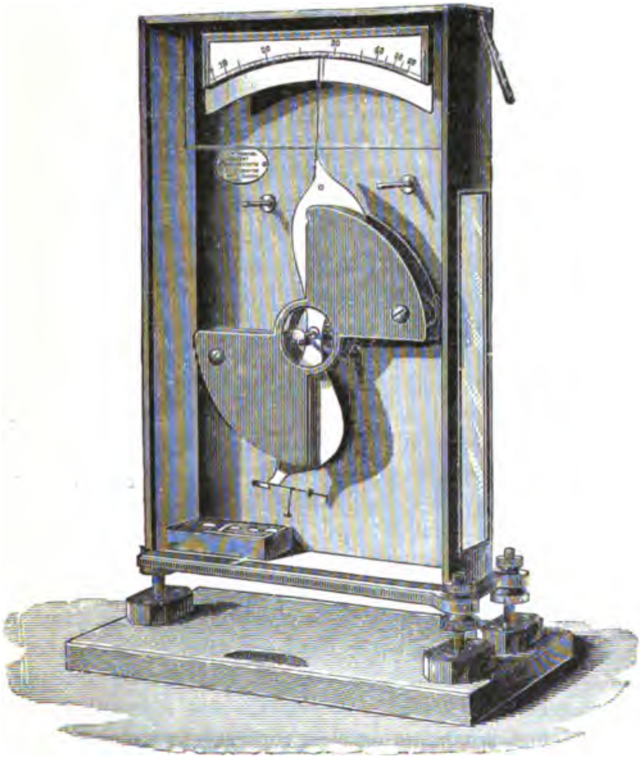
6 watts. This subsidiary resistance coil is composed of silk-covered platinoid wire, which is wound on a vulcanized fibre frame and placed inside the brass case of the instrument.

The outer iron sleeve, which it will be remembered fits friction-tight on the brass tube, is the principal adjustable part of the instrument; by turning it round so as to vary the force with which the needle is acted upon at different points, the instrument can be adapted for use as a voltmeter or as an ammeter at will, or the scale may be made open or close at any desired part.

In the recent development of electric lighting the tendency is towards the use of very great differences of potential, much greater than any we have hitherto considered. These potential differences are alternating, thus excluding at once a large number of measuring instruments; and it will readily be conceived that even those which we have described as capable of measuring alternating potential differences could not well be modified so as to measure up to 10,000 or even 2,000 volts. A voltmeter has been designed by Lord Kelvin, based upon the well-known elementary fact that two adjacent bodies at different potentials mutually attract each other. We have seen that a simple way of establishing this difference of potential is to rub two dissimilar substances, such as a piece of flannel and a piece of sealing-wax, together; they will then mutually attract each other, and the force of this attraction might serve to estimate the potential difference between them. Now, there is a difference of potential between the two poles of a battery, and if these two poles are connected one to each of two insulated metal conductors (say brass spheres), the spheres will be at different potentials and will attract each other; this force of attraction is, however, too feeble to cause any perceptible movement, unless very delicate refinements, unsuitable for workshop use, are resorted to. But for this latter fact, such a method of measuring potential difference would be perfect in one respect, for, as the two conductors are insulated, no current whatever would flow from the battery, and we might therefore measure the potential difference without altering it during the act of measurement. The use of this 'electrostatic' method, however, becomes practicable in the case of several hundred volts, and fig. 111 shows one form of Lord Kelvin's voltmeter which is based upon it.

One conductor is fixed and the other movable; the fixed one consists of two butterfly-shaped sheets of brass, parallel to each other, and metallically connected, but carefully insulated from the rest of the instrument. The movable conductor is a thin aluminium strip, supported at its centre on a knife-edge, and moving

FIG. 111.



freely in a vertical plane exactly midway between the two fixed brass plates. When at rest the movable plate or strip is kept in a vertical position by very small weights placed on a knife-edge at its lower extremity. If a difference of potential is established between the fixed plates and the movable strip, mutual attraction

results, and the latter tends to set itself in a position, as far as possible, inside the fixed plates, this tendency being counteracted by the weights which it carries. The force of attraction is proportional to the square of the potential difference; the movable conductor, of course, comes to rest when the forces due to the electrostatic attraction and to gravity balance one another, and this position of rest is indicated by a light pointer moving over a graduated scale. This scale has 60 divisions, which represent equal differences of potential, and a large range is obtained by varying the balancing weights, three weights being supplied with every instrument. The actual value in volts of the potential difference competent to move the pointer through one division will, of course, depend upon the weight suspended at the lower part of the movable plate. With the particular instrument illustrated one division corresponds to 50 volts when the lightest weight is employed; twice the potential difference is required to produce the same effect when the next weight is added, or one division then represents 100 volts; while when all the three weights are employed, one division corresponds to 200 volts, so that the maximum potential difference indicated by this particular instrument is $200 \times 60 = 12{,}000$ volts.

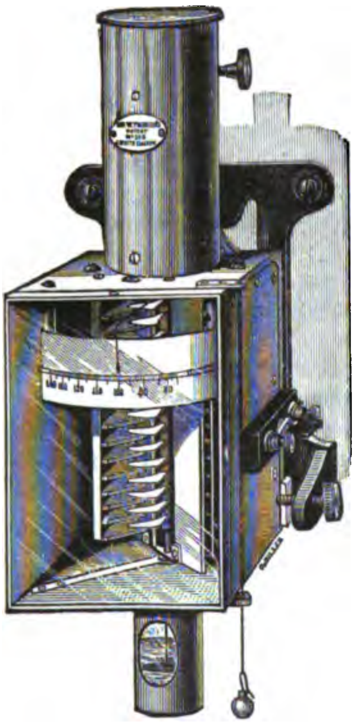
The case enclosing the conductors is of metal with a glass front, and the movable conductor is electrically connected by means of the knife-edges to this metallic case, which is provided with a suitable terminal screw. The knife-edges afford a sufficiently good connection in this instance, since they are not required to carry a current. The fixed brass plates are connected to a second terminal, which is carefully insulated from the case. The whole instrument is effectively insulated from earth by means of the stand upon which it is placed, and in order to measure the potential difference between two conductors it is only necessary to connect one conductor to one terminal and the other to the other terminal and observe the reading of the pointer, with the appropriate weights on the bottom of the 'needle.' It is almost unnecessary to add that too much care cannot be exercised in the measurement of high potential differences, and as a matter of fact no one should attempt any such measurements except after a considerable amount of experience under the direction of a

qualified instructor, who must of course himself be an expert at the work. Where the apparatus is permanently fixed for constant use it may be protected by an insulating cover with a glass front; but it is during the making of changes, or during experimental work, that an accident is likely to occur. In some instances one of the two conductors between which a potential difference is to be measured is connected to earth, and this conductor should invariably be joined to the 'needle' and metallic case, and then should the case be touched by the experimenter he would experience no shock, because both the case and his body are earth-connected, and are therefore at the same potential. No part of the instrument, however, should be so touched while any 'live' conductor is connected to it, as such an action partakes of the nature of a test for the efficiency of the earth connection, which *might* be defective, and it also begets carelessness when using the apparatus under other conditions.

For accurately measuring lower potential differences the instrument cannot be made in such a simple form, as with one movable metallic strip it would be difficult to obtain a sufficiently great force of attraction. The requisite attractive force can, however, be obtained by employing a greater number of 'needles' or vanes, each moving between a pair of fixed conductors, and such an instrument is called a 'multicellular' electrostatic voltmeter. Fig. 112 illustrates such a voltmeter designed to measure from 80 to 140 volts. The aluminium vanes (15 in number) are horizontal and equidistant, being fixed on a vertical spindle, and all in metallic connection. This spindle is supported by a platinum-iridium wire, which is set so that the pointer stands at zero when no electrical difference exists between the vanes and the rest of the instrument. The pointer is rigidly attached to the spindle, and is bent over at right angles so that its free end passes in front of a curved vertical scale calibrated to read directly in volts. The fixed conductors between which the aluminium vanes play are triangular brass plates fixed into vertical brass plates, all connected together, but insulated from the outer brass case of the instrument. Only one set of vanes and plates is distinctly visible in the figure, but there is a corresponding set on the opposite side of the spindle, lying further back in the case to the right-hand side. The fixed brass

plates are connected to an insulated terminal on the side of the case, and the spindle carrying the aluminium vanes is connected to the case by means of the platinum-iridium suspending wire. When a difference of potential is set up between the fixed and movable conductors, the attractive force urges the latter to take up a position inside the former, thus giving a rotary motion to the vertical spindle. The torsion thus put on the suspending wire works against this force, and the point at which the two forces balance, as indicated by the pointer, shows the potential difference. Suitable guiding holes through which the spindle passes, and two vertical brass plates (one of which is seen to the right in the figure) limit the movements of the spindle and prevent contact between the two sets of conductors under all circumstances, while a vane carried on an extension of the spindle moves in an oil dash-pot below the case and steadies the movements of the moving parts.

FIG. 112.



Since an electrostatic voltmeter allows no current to pass between the two points whose potential difference it indicates, there is no possible chance of any error similar to that due to the heating of the coils in an electro-magnetic voltmeter. Further, there is no waste of energy as in the latter case, and an electrostatic instrument may therefore be kept permanently connected between the two mains of an electric light circuit without adding to the coal bill.

Another important feature common to instruments of this type

is that they may be used to measure either steady or alternating potential differences with equal facility. In an electro-magnetic voltmeter the indications of the needle are dependent upon the strength of the current flowing through the coil, which should vary exactly with the pressure between the ends of the coil; and with a steady uni-directional pressure this proportional variation does take place, because the resistance of the coil (supposing the heating effect to be negligible) remains constant. But with an alternating potential difference the value of the resulting alternating current depends upon the 'self induction' as well as the resistance of the coil, and the effect of the self-induction changes with the rate at which the current alternates. Consequently, although an electro-magnetic voltmeter may be calibrated to indicate correctly for a certain rate of alternation, it will not necessarily be correct for any other rate of alternation. An electrostatic instrument being quite free from any self-induction effect is independent of the rate of alternation. Moreover, since the instrument is calibrated to read in volts, while the force of attraction between the plates varies as the square of the potential difference, it indicates directly the value of the square root of the mean square of the potential difference between the plates, which, as the student will presently learn, is the value generally required to be known.

There are many other forms of electrostatic voltmeters, all of which are, however, similar in principle to those described, and no difficulty should be experienced in understanding their construction and action. In some cases a small mirror is attached to the movable conductor, and the mirror reflects a luminous beam on to a scale placed in front of it. The movements of the spot of light indicate the deflections of the needle, and therefore also the potential difference which causes those movements.

CHAPTER VII.

ELECTRO-MAGNETS—ELECTRO-MAGNETIC INDUCTION

It has been observed that the air space in the neighbourhood of a wire, in which the effect of a current travelling in the wire is perceptible, is called an electro-magnetic field, and that the direction in which the force in this field acts can be made evident by means of iron filings, which, if sprinkled upon a sheet of paper with the wire passing through it, arrange themselves in concentric circles along the lines of force round the wire. And further, it will be remembered that some substances offer greater facilities than others for the propagation of these lines of force, and that it is possible to alter their circular form by bringing near them some substance through which they pass with either more or less ease than through the air. The relative capability possessed by any substance for conducting these lines of force is known as its 'permeability,' and it is obviously desirable that some method of definitely comparing this property in various bodies should be adopted. The permeability of air[1] can be taken as the standard, and the permeability of all other substances measured by comparison with it.

If a piece of hard steel is placed in any magnetic field, many of the adjacent lines of force are bent out of their previous shape, and converge into the steel. More lines of force, therefore, pass through the space occupied by the steel than passed through that same space when occupied by air alone. Hence we conclude that the lines of force pass through steel more readily than through air, or the permeability of steel is greater than that of air. If, again, the steel is replaced by a piece of soft iron of similar shape and size, even more lines of force will now pass through the same

[1] The permeability of a vacuum is taken as unity; that of air is almost exactly the same, and is a more convenient standard.

space, showing that the permeability of soft iron is still greater than that of steel. In fact, the permeability of any substance might be measured by dividing the number of lines of force which pass through it by the number which pass through the same space when the substance is removed, the strength of the magnetising field being the same in both cases. There is, however, no method available for determining the actual number of lines of force pervading any particular space or substance. The nearest approach to such a desideratum would be to measure the relative strength of any electro-magnetic field, or of any given portion of it, because, as might be supposed, the strength of the field varies directly as the number of lines of force pervading it. It is possible to compare the strength of fields by measuring the magnitude of various phenomena which can be made to take place in them, and one such method is described at the end of this chapter.

We can by such means measure the strength of a field due to any magnetising force—that is, the number of lines of force passing through any given air space—and then, filling that same space with a piece of iron, measure the relative number then passing through the iron. The number of lines of force passing through an area of one square centimetre taken at right angles to them is called the 'magnetic induction,' the term being employed as an abbreviation for 'intensity of magnetic induction;' the magnetic induction through the air space is equal to the strength of the magnetising field (since the permeability of air is 1), and the magnetic induction through the iron, divided by the strength of the magnetising field, gives the permeability of the iron.

By experimenting in this way it has been proved beyond doubt that not only do different substances possess various degrees of permeability, but also that this property may vary considerably in the same substance under certain conditions; and it is also possible to arrange the various substances in the order of their relative degrees of permeability. The most permeable material known is pure soft iron, and it is found that, generally speaking, as the hardness and impurity of the iron increase, so its permeability decreases; that of hard steel, cobalt, and nickel, and especially of a certain kind of manganese steel; being comparatively low. The vast majority of substances, including most of the other metals,

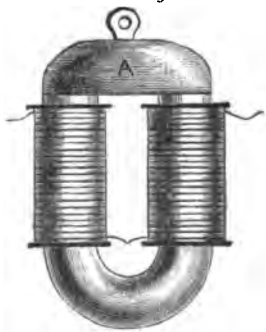
are to all intents and purposes equal to air in this respect, while the permeability of a few metals, including bismuth and copper, is very slightly less than that of air. To take the two extreme cases, the permeability of iron has been known to exceed 2,000—that is to say, 2,000 times as many lines of force have been known to pass through a certain piece of iron as passed through the equivalent air space when the iron was absent, while that of bismuth has not been found to be much below 0·9999.

This property is very important in some practical operations, and (especially in the case of iron) it is useful to know the conditions under which it varies in the same material. We have already touched upon a practical application in the case of a helix or solenoid, and are now in a position to further consider the matter. We observed that the electro-magnetic effect of a helix carrying a current can be increased in two ways—either by increasing the strength of the current and so increasing the actual number of lines of force produced, whatever that number may be, or by increasing the effect of the available lines of force by making as many of them as possible pass through that space near the ends, where they will be able to act to the greatest advantage. The permeability of bismuth and copper being less than that of air, either of these substances, when placed in an electro-magnetic field, will *decrease* the number of lines of force passing through the space which it occupies; but even in the case of the most effective substance known, viz. bismuth, the difference is so very slight that it is difficult to perceive or measure it. If, however, any substance were to be discovered with a permeability very much less than that of air, one way of leading the lines of force through the desired space would be to place this substance of low permeability in that part of the field from which it is wished to exclude those lines—that is to say, to make all paths but the right one, or the one desired, as difficult as possible. But the permeability even of bismuth being so little inferior to that of air, the only available method of attaining the desired end is to make the path which it is desired the lines of force should take, as easy as possible. In the case of the solenoid described in Chapter IV. we wished to increase its effect by leading as many as possible of the lines of force through the ends of the coil, instead of allowing them to leak

out at the sides, and for this purpose fitted it with a soft iron core, which had the desired effect. Since the permeability of different qualities of iron varies so much, too great care cannot be exercised in its selection ; and, experiment having shown that soft annealed Swedish iron is superior to all other kinds, this should, when the question of expense does not forbid, be used in all cases where it is desired to concentrate the lines of force at any particular point. The best Swedish iron is, however, somewhat difficult to obtain, and the same remark applies to the very best Yorkshire brands (Bowling, Lowmoor, &c.), which are scarcely inferior to Swedish iron. Although for some small machines and instruments it is imperative to employ the best iron procurable, yet for heavier machines it is frequently cheaper to employ a slightly inferior iron, and use a greater quantity of iron and of wire to obtain the desired result.

It will be remembered that a helix of wire fitted with an iron core is called an electro-magnet, and electro-magnets differ in shape and arrangement according to the work they are intended to perform. Thus, if it were wished with one pole of an electro-magnet to repel a similar pole of another electro-magnet, or of a permanent steel magnet, with as much force as possible, it should be made long and straight, so that its opposite pole might be as far away as practicable. It frequently happens, however, that an electro-magnet is required either to support a heavy weight or to attract another magnet or a piece of iron as powerfully as possible. It is then more advantageous to allow both poles of the electro-magnet to act together, and this can be accomplished by making it somewhat similar in shape to a horse-shoe, and so bringing the poles close together, as is the case in fig. 113, winding the wire only over the 'legs' of the iron core.

FIG. 113.



In designing an electro-magnet, therefore, the object to which it is intended to apply the apparatus must be kept clearly in view, and it is necessary that the general principles underlying electro-

magnetic construction should be now considered, although, under the most favourable circumstances, these laws and principles are somewhat complicated and involved, and, to a great extent, indeterminate.

In the generation of an electro-magnetic field by means of a solenoid there are two prime features to be taken into consideration—viz. the strength of the current and the number of convolutions of wire constituting the coil. It can readily be understood that the electro-magnetic effect produced by a current varies directly as the strength of that current, so that to double the intensity of the field developed by any particular coil it will suffice to double the current strength. There is, therefore, no need to take into account the resistance of the wire, except in so far as it may modify the current strength, the resistance varying, of course, directly as the length, and inversely as the square of the diameter, of the wire.

As the current strength in any circuit is the same in all parts, or at all points, of that circuit, the electro-magnetic field developed by any unit length—say one inch of the wire—is exactly equal to that developed by any other portion of the circuit of equal length. It follows, therefore, that two convolutions or turns of wire close together will generate a field twice as strong as that which can be developed by either of the turns taken separately; and, speaking generally, it can be said that the field developed by a solenoid varies in strength directly as the number of convolutions, and this will be true whatever the nature of the material forming the conductor, or whatever its resistance.

In order to arrive at a more precise understanding, let us again consider the problem set us, supposing we desire to make an electro-magnet similar to that illustrated in fig. 113 as effective as possible. The object is to attract the 'armature,' A, with the maximum force, and in order to attain this result we want to urge as many lines of force as we possibly can through that armature.

Now, when we wish to calculate the strength of a current of electricity which will be obtained in any given electrical circuit under certain conditions, we take into account the electro-motive force which urges the current, and the resistance against which that electro-motive force has to act, the resulting current being

directly proportional to the former and inversely proportional to the latter, and write

$$\text{Current strength} = \frac{\text{Electro-motive-force}}{\text{Resistance}}.$$

Somewhat similarly we may consider the whole path round which we desire to urge magnetic lines of force as a magnetic circuit, and take account of the total magnetising force which tends to urge the lines of force round the circuit as well as the 'magnetic resistance' against which that force must act in order to produce the result. Then we may say

$$\text{Total number of lines of force} = \frac{\text{Magneto-motive force}}{\text{Magnetic resistance}},$$

where the term magneto-motive force represents the total magnetising force acting round the whole circuit. This magneto-motive force is for any magnetic circuit *proportional* to the current strength and to the number of convolutions in the solenoid—that is to say, to the 'ampere-turns,' as was mentioned above in the general view of the case. But in order to adapt all results to the C.G.S. system of measurement we unfortunately require to introduce other factors. In the first place the C.G.S. unit of current is equal to 10 amperes, so that, the C.G.S. unit of current being adopted in the fundamental calculations, the ampere-turns must be divided by 10; and then, for reasons which cannot be simply stated, we must multiply the ampere-turns by 4π. If, then, we denote the strength of the current as measured in amperes by C, and the total number of convolutions by N, the magneto-motive force will be equal to $\frac{4\pi \times C \times N}{10}$, or $1{\cdot}2566 \times C \times N$.

We must now consider the question of the magnetic resistance offered to this magneto-motive force, and here again an analogy with the electrical circuit may help us, although the two cases are not strictly analogous. The resistance of a simple electrical circuit varies directly as the length of the circuit, l, inversely as the sectional area of the conductor, a, and inversely also as the specific conductivity of the conductor, m, specific

conductivity being the inverse of specific resistance. This may be stated as :

$$\text{Resistance} = \frac{l}{a \times m}.$$

In a magnetic circuit permeability, or the relative capability of conducting lines of force, is analogous to electrical specific conductivity ; and the magnetic resistance also is directly proportional to the length of the circuit, l, and inversely proportional to the sectional area, a.

Consequently,

$$\text{Magnetic resistance} = \frac{l}{a \times \mu},$$

l being preferably measured in centimetres, a in square centimetres, and μ standing for the permeability of the substance of which the magnetic circuit is composed.

In order, therefore, to calculate the number of lines of force flowing round any circuit, which number we may conveniently denote by **N**, we may say

$$\mathbf{N} = \frac{\text{magneto-motive force}}{\text{magnetic resistance}},$$

that is

$$\mathbf{N} = \frac{\dfrac{4\pi \times \text{C} \times \text{N}}{10}}{\dfrac{l}{a \times \mu}},$$

or

$$\mathbf{N} = \frac{1{\cdot}2566 \times \text{C} \times \text{N} \times a \times \mu}{l},$$

where C represents the current strength in amperes, and N the total number of convolutions in the solenoid.

The matter may, perhaps, be rendered clearer by assuming a set of conditions for the electro-magnet depicted in fig. 113. Suppose the number of convolutions on each limb to be 200 ; then $\text{N} = 2 \times 200 = 400$; and that the current strength is 80 milliamperes, or ·08 ampere. Let the mean length of the magnetic circuit (that is, the length measured round the circuit through the middle of the core and armature) be $l = 12$ centimetres, and the area of the core and armature at any point be $a = 3$ square centi-

metres. The permeability of the iron will vary with the number of lines of force which pass through it, but we will assume it to be $\mu = 500$.

Then in this case

$$N = \frac{1 \cdot 2566 \times \cdot 08 \times 400 \times 3 \times 500}{12} = 5{,}026;$$

that is to say, if we could at any point cut the magnetic circuit without disturbing the arrangement, we should find 5,026 lines of force passing across between the two faces of iron so separated.

Unfortunately, we do not find the problem quite so easy in actual practice. We have here ignored the fact that some of the lines of force would leak out from the iron, and not pass completely round the desired path. Further, although the armature and pole faces may be accurately faced up and fit truly, the two joints in the magnetic circuit will make the magnetic resistance appreciably higher than it would be were the fibre of the iron continuous throughout.

Were the armature to be separated from and fixed at a little distance (say 1 centimetre) from the pole faces, a vast increase in the magnetic resistance would take place, causing a corresponding reduction in the number of lines of force passing through the armature, and hence a diminished force of attraction. The resistance of each air gap would be $\frac{l}{a \times \mu} = \frac{1}{3 \times 1} = \frac{1}{3}$, the value of μ being 1 for air, so that $\frac{2}{3}$ would have to be added to the resistance of the magnetic circuit. In addition to this, the leakage would be greatly increased, many of the lines of force passing across the air space between the two magnet limbs instead of through the armature, and this also would have to be allowed for, as will be presently shown.

It is frequently convenient to speak of the intensity of the magnetising force at any point, instead of the magneto-motive force or total magnetising force, and the value of this intensity at a point is denoted by the symbol **H**. It is measured by the force in dynes with which a magnet-pole of unit strength would be acted on at the point in question, and obviously may vary considerably at different points round a complex magnetic circuit.

If we consider the case of a long straight evenly wound solenoid, the value of H will be practically uniform inside it along its whole length except just at the ends, and it will evidently vary with the density of the convolutions of wire, or the number per unit of length of the solenoid. The value of H will in fact be $\frac{4\pi C \times n}{10}$ dynes, where C is the current strength in amperes, and n the number of convolutions per unit of length of the solenoid. Thus, if with the same length of wire the solenoid were uniformly stretched or re-wound so as to become double its original length, the value of H at any point would be halved, because the number of convolutions per unit of length would be halved. But the total number of convolutions, N, is unaltered, and hence the value of the magneto-motive force is the same as before. It is evident that if a uniformly wound solenoid contains n convolutions per centimetre, and is l centimetres in length, the value of the magneto-motive force is equal to $H \times l$; or, the magnetic force at a point, H, may be found by dividing the magneto-motive force (that is, the total magnetising force) by l, the length of the solenoid. The case is rendered clearer and more exact if we take a solenoid wound uniformly over a non-magnetic tubular ring. If the solenoid had n convolutions per centimetre, and the mean circumference of the ring were l centimetres, then a unit magnet-pole would experience a force of $H = \frac{4\pi C n}{10}$ dynes at any point in the interior of the solenoid, and it would require the expenditure of H ergs of energy to move it through a distance of one centimetre against the magnetising force, and therefore $H \times l$ ergs to move it all the way round the solenoid, $H \times l$ being thus a measure of the magneto-motive force. Let the diameter of the ring be now increased sufficiently to double its mean circumference, then the convolutions will be half as dense as before, being only $\frac{n}{2}$ per centimetre, and consequently the value of H will be halved. But the distance through which the magnet-pole must be moved to make the complete journey has been doubled, and therefore the total expenditure of energy is still $\frac{H}{2} \times 2\,l$

$= \mathbf{H} \times l$ ergs, proving the magneto-motive force to be the same as before.

It is also sometimes necessary to specify the density of the lines of force at any given point, or the number passing through a square centimetre whose plane is at right angles to the direction of the lines, and this density is denoted by the symbol **B**. If the magnetic circuit be not perfectly uniform throughout, the value of **B** may differ considerably at different parts thereof. Thus, supposing the armature to be entirely removed from the electro-magnet shown in fig. 113, most of the lines of force would pass as far as possible through the iron core, and would be approximately equally dense at all parts thereof except near the poles. Here they would begin to leak out at the sides of the iron core instead of all passing out through the ends or pole-faces, and in crossing from one pole to the other through the air space they would spread out in all directions. The value of **B**, then, would be rather less in the iron near the pole-faces than at the bend and inside the solenoids, while it would be comparatively small in the air space.

If we took an iron ring and wound it uniformly with wire, through which a current was made to flow, practically all of the lines of force would make the complete circuit through the continuous iron ring, and the value of **B** would be the same at all parts thereof. Suppose the area of cross-section of the iron to be three square centimetres, and the total number of lines of force **N** to be 27,000, then the value of **B** at any point would be $\frac{\mathbf{N}}{3} = 9{,}000$. If the iron core were removed, we may suppose the value of **B** to fall to 15, that is, 15 lines of force per square centimetre, and we thus obtain a measure of the increase in the number of lines of force due to the presence of the iron core, which, as we know, measures the 'permeability' of the iron. If the interior of the solenoid is occupied by air or any other non-magnetic substance, a magnetising force of value **H** can produce **H** lines of force per square centimetre, and **H** is in air equal to **B**. By the addition of an iron core **B** increases but **H** remains unaltered, and the permeability of the iron

$$\mu = \frac{\mathbf{B}}{\mathbf{H}}.$$

In the instance just mentioned, then, the permeability of the iron would be $\frac{9000}{15} = 600$ under the existing conditions.

The best way of ascertaining the manner in which the values of **B** and μ vary in any given sample of iron or steel for different values of the magnetising force **H**, is to experimentally determine the value of **B** for a number of values of **H** from zero upwards, and the results are conveniently shown by plotting curves. This subject will be referred to at the close of this chapter.

It will be observed that by simply increasing the diameter of an iron core, and also the diameter of the convolutions of the helix surrounding it, we do not alter the value of **H** or **B** provided the current strength remains constant, because, although we thereby increase **N**, the total number of lines of force, the corresponding increase in the area of the core leaves the density the same as before.

It must be remembered, however, that, supposing the electromotive force available to be a fixed quantity, any increase or decrease in the diameter of the coil must proportionally increase or decrease the length of the wire and its resistance, and cause thereby a decrease or increase in the current strength, unless this variation in the length of wire is accompanied by a corresponding variation in its cross-section, so as to keep the resistance constant.

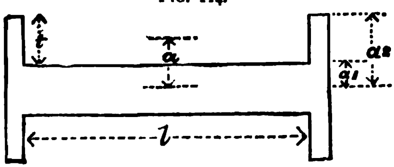
Again, supposing the dimensions of the core be kept constant, and that it is desired to more strongly magnetise it by adding to the number of convolutions, care must be taken that in this instance also the current strength is kept constant by a corresponding increase in the potential difference at the ends of the coil. Were the potential difference to remain unaltered, the additional layers would not bring about any increased magnetisation of the core. For example, if the number of convolutions were doubled, the resistance of the coil would also be doubled, and the current therein halved, so that the ampere-turns would remain unaltered. If a coil consists of a number of layers, it must be remembered that the length of the wire in the outer layers will be appreciably greater than in the inner. To take an extreme case, we will suppose the coil to consist of ninety-nine layers, in which

case the length of wire composing the ninety-ninth layer would be considerably greater than that forming the first. Now, the circumference of a circle varies directly as its diameter, and is equal to $2 \pi r$, where π is the ratio between the circumference of a circle and its diameter (or 3·1416), and r is the radius of the circle. If, therefore, the diameter of the outside layer is actually twice that of the inside, the length of the wire in each of the larger turns, and consequently in the whole layer, will be exactly doubled, and its resistance doubled also; and the intermediate layers will vary proportionately. But the actual resistance of the whole coil can be easily calculated, for if the radius of the inside layer, the resistance of which is, say, 5 ohms, is half an inch and that of the outside layer one inch, the mean or average radius will be three-quarters of an inch—that is to say, the length of wire in the fiftieth layer will be half as long again as that in the first. Its resistance will therefore be 7·5 ohms. Similarly, the resistance of the first and last layers together will be 15 ohms, or an average of 7·5 ohms per layer, and this will be true of every similarly situated pair of layers, so that the total resistance of a number of layers is equal to the resistance of the middle or average layer multiplied by the number of layers. In the coil under consideration the resistance will be

$$\text{R} = 7{\cdot}5 \times 99 = 742{\cdot}5''.$$

When the field due to a certain coil, consisting of many layers, is insufficient for a given purpose, it may become advantageous to re-wind the bobbin with wire of a smaller gauge, so as to get a greater number of turns into the same compass. A reference to the diagram, fig. 114, will simplify some of the difficulties involved in a consideration of this matter. Let us suppose the figure to represent a wooden or ebonite bobbin, and that the length, l, of the space occupied by the coil, or the distance between the 'cheeks' of the bobbin, is 3 inches, while the radius, a_1, of the bottom layer to be wound is a quarter of an inch, and the extreme

FIG. 114.



radius, a_2, of the coil three-quarters of an inch. The mean radius, a, will be half an inch, or

$$a = \frac{a_1 + a_2}{2} = \cdot 5.$$

The total thickness, t, of the coil or of the layers will also be half an inch, or

$$t = a_2 - a_1 = \cdot 5.$$

As we have already seen, the length of one turn of wire of radius a_1 will be $2 \pi a_1$, and, if there are n turns in that layer, the length of wire comprised in it will be $2 \pi a_1 \times n$. Supposing there to be m layers in the coil, having the mean radius a, the total length L will be

$$\text{L} = 2 \pi a \times n \times m \quad . \quad . \quad . \quad . \quad . \quad . \quad (1).$$

Now, as, in winding a number of layers of wire in a coil, each turn must somewhere or other *cross* the subjacent turn, it follows that the turns of any one layer cannot be placed evenly in the grooves or recesses between the turns of the layer immediately underneath it; or, in other words, if we assume the wire, with its insulating covering, to have a diameter, d, the section of the space occupied or appropriated by that wire will really be a square whose side is equal to d. Consequently, in one layer the number of turns n will be

$$n = \frac{l}{d},$$

and the number of layers, m, will be

$$m = \frac{t}{d}.$$

Substituting these values for m and n in (1) we get

$$\text{L} = 2 \pi a \times \frac{l}{d} \times \frac{t}{d} = \frac{2 \pi a \times l \times t}{d^2} \quad . \quad . \quad . \quad (2).$$

For example, let the diameter of the wire, with its insulating coating, be 50 mils (the mil is the thousandth part of an inch), then the length of this wire that would be required to fill the bobbin illustrated in fig. 114 would be

$$\text{L} = \frac{2(3{\cdot}1416) \times 0{\cdot}5 \times 3 \times 0{\cdot}5}{(0{\cdot}05)^2} = 1885 \text{ inches} = 52\tfrac{1}{3} \text{ yards}.$$

We are thus able to calculate not only the length of wire required to fill any bobbin, but also its resistance, the resistance per unit of length being ascertainable from tables. Moreover, the total number of turns of wire can be easily calculated, for, m being the number of layers, and n the number of turns in each layer, the product $m\,n$ will give the total required, but

$$m = \frac{t}{d}, \text{ and } n = \frac{l}{d};$$

$$\therefore m\,n = \frac{tl}{d^2},$$

$$\text{or } m\,n = \frac{0{\cdot}5 \times 3}{(0{\cdot}05)^2} = 600 \text{ turns.}$$

Let it now be supposed that a given bobbin—say of the dimensions shown in fig. 114—is to be filled with copper wire which shall offer a definite resistance, say 5 ohms. There are thus only three quantities known, viz. the dimensions of the bobbin, the resistance which the coil is to offer, and the specific resistance of the copper; while the length of the wire and its diameter are unknown and require to be ascertained. The space in which the wire is to be wound can be calculated from the given dimensions, for, V being this space or volume,

$$V = \pi\, l(a_2^2 - a_1^2) \quad \text{. . . . . (1).}$$

$$\text{or } V = 3{\cdot}1416 \times 3({\cdot}75^2 - {\cdot}25^2)$$

$$= 4{\cdot}712 \text{ cubic inches.}$$

But supposing, as will be actually the case, that the wire, whose diameter is d, occupies the same space that it would take were it to be square instead of round, then, manifestly,

$$V = L \times d^2 \quad \text{. . . . . (2).}$$

As, also, the total resistance of the wire varies directly as its length, directly as its specific resistance s (which, in this case, as the other dimensions are in inches, we take as the resistance between opposite faces of an inch cube), and inversely as the area or cross-section of the wire,

$$R = \frac{L \times s}{area}.$$

But the area of the insulated wire is equal to πr^2, or $\pi\left(\frac{d}{2}\right)^2$, that is, $\pi\frac{d^2}{4}$.

Therefore $$R = \frac{L \times s}{\pi\frac{d^2}{4}},$$

that is, $$R\,\pi\frac{d^2}{4} = L\,s,$$

or, $$R\,\pi\,d^2 = 4\,L\,s,$$

and $$d^2 = \frac{4\,L\,s}{R\,\pi} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3).$$

But from (2) it will also be seen that

$$d^2 = \frac{V}{L} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4).$$

Consequently $$\frac{4\,L\,s}{R\,\pi} = \frac{V}{L} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5).$$

and $$4\,L^2\,s = \pi\,R\,V.$$

Therefore $$L^2 = \frac{\pi\,R\,V}{4\,s},$$

and, finally, $$L = \sqrt{\frac{\pi\,R\,V}{4\,s}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6).$$

By inserting the numerical values on the right-hand side of this equation, the length L, having the required resistance, can therefore be found, after which we can, by equation (4), determine also the gauge of the wire. It must, however, be noted that, for simplicity, d is taken as the diameter of the bare wire in equation (2), thus rendering the result only approximate; but when the thickness of the wire is great as compared with that of the insulation, the formulæ approach very closely to the truth.

It is frequently useful to know the exact length of any particular wire which can be wound on any particular bobbin, and, knowing V and d, this can be easily ascertained, for, if d_1 represents the outer diameter of the wire and its covering, V the volume of the wire-space, and L the required length, then

$$L = \frac{V}{d_1^2}.$$

Returning now to the consideration of the core of an electro-magnet, it is evident that, generally speaking, it is advantageous to make the magnetic resistance of the magnetic circuit as low as practicable, in order to obtain the requisite number of lines of force with the minimum magneto-motive-force; and, consequently, the three factors, length, sectional area, and permeability, should receive due consideration in determining the dimensions of the core and the material of which it is to be composed.

If, as is sometimes the case, lightness and compactness are important, then it is essential to employ for the core annealed wrought iron of high permeability, as then the desired effect can be obtained with the minimum sectional area. But should the question of weight be of secondary importance, iron of lower permeability—even cast iron—may be employed. For example, in the case of the massive cores for the field magnets of dynamo machines, the requisite quantity of the highest quality wrought iron is not only expensive as regards first cost, but it requires a further and considerable expenditure upon it in forging and machining it up to the proper shape and dimensions for fitting the parts together and to form the cavity for the reception of the rotating armature. Cast iron is not only cheaper, but the material may be cast to such a shape that it requires but little further work on it; and by sufficiently increasing the sectional area of the core over and above that which would be required if it were made of wrought iron, the lower permeability is compensated for. It should be remarked, however, that such an increase in the sectional area of the core necessitates the employment of a correspondingly greater quantity of copper wire for the magnetising coil, for each convolution is, of course, increased in length, and in many cases must also be increased in thickness to prevent the greater length increasing the resistance of the coil. Mild steel promises to combine the good features of wrought iron and cast iron for heavy electro-magnet cores, for it can be cast into moulds as readily as cast iron, while some qualities have a permeability not far short of that possessed by the best wrought iron. Such mild steel contains a very small percentage of carbon, and cannot be hardened and tempered like tool-steel, which contains a much greater proportion of carbon, and has a correspondingly lower permeability. Mild

steel, in fact, is, in its chemical composition, practically similar to wrought iron, although it is crystalline in its structure, on account of the fact that its particles settle down under no external restraining force when the metal solidifies from the molten state in which it is manufactured. This crystallinity can be somewhat reduced by hammering and rolling, and it is absent in good wrought iron which has been hammered and rolled while cooling from a high temperature until it is fibrous throughout. Even wrought iron, if raised to a very high temperature and then allowed to cool in the absence of these mechanical restraining forces, becomes crystalline, and loses to a great extent its valuable mechanical and magnetic qualities.

It is evident that before the dimensions of the core of an electro-magnet, such as that employed for a dynamo field-magnet, can be decided upon, it is necessary to know the permeability of the metal which is to be employed for the purpose. Further, since the permeability of iron or steel varies considerably with the density of the lines of force passing through it, that is to say, with the value of **B**, it is also necessary to decide upon the maximum density at which the core is to be worked. If a piece of iron destitute of magnetisation be experimented upon, by observing the number of lines of force obtained through it with a number of gradually increasing values of magnetising force, it will be found that the effect of projecting a *few* lines of force through the iron is to slightly raise the value of its permeability, but after a certain number of lines have been urged through the iron the permeability rapidly diminishes in value, and beyond a certain point a considerable increase in the magnetising force makes but little difference in the value of **B**. When it thus becomes very difficult to urge additional lines of force through a piece of iron, it is said to be magnetically 'saturated,' but no definite point has yet been reached at which it can be said to be absolutely impossible to increase the number. Professor Ewing has succeeded in forcing 45,350 lines of force per square centimetre through a sample of the best Yorkshire (Lowmoor) iron; but in order to obtain this result a magnetising force of no less value than **H** = 24,500 had to be employed, and the permeability, μ, was thereby reduced to 1·85, or the iron in this condition was less than twice as permeable

as air. This result was obtained by turning a cylinder of iron down in the middle of its length and tapering out to the ends, so that it consisted of two cones joined together by a narrow cylindrical neck, the high induction mentioned being obtained in the narrow neck when the base of each cone lay against one pole-face of a powerful electro-magnet. In practice we should not, of course, work with anything approaching to these figures, but should be content with a value of **B** where the metal was approaching the saturation point, which may be taken as approximately 16,000 to 17,000 for the best wrought iron.

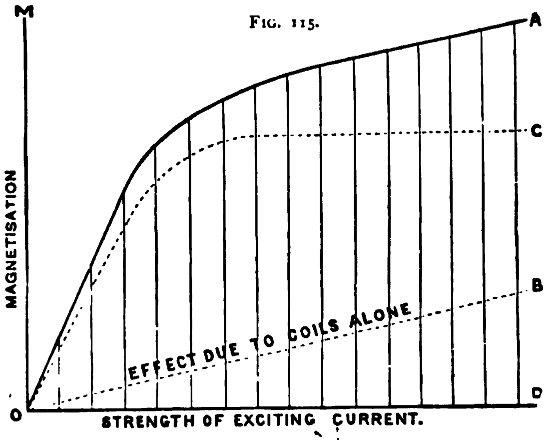
A simple method for determining approximately the manner in which the value of the magnetic induction in, say, a soft iron rod varies for different values of the magnetising force may now be considered.

Suppose the rod to be long compared with its diameter, we may fix it in a vertical position, with its upper end on a level with, and at a convenient distance from, a suspended magnetic needle, and note, by the deflections of the needle from its zero position, the manner in which the magnetisation of the rod increases or diminishes. The needle should preferably be a small piece of watch-spring, magnetised, cemented on to the back of a small circular mirror, and suspended by a silk fibre, mounted, in order to shield it from air currents, in a small glass-fronted case. A beam of light can be made to fall on the mirror, and the reflected beam falling on a scale, the movements of the spot of light so formed can be made to indicate with great exactness every movement of the needle. The iron rod being of considerable length, its lower end will be so far away that it will have practically no effect on the needle. If a coil of wire be wound over the rod, currents of gradually increasing strength can be sent through the coil, and the magnetising force being proportional in every case to the current strength, while the deflections of the needle are approximately proportional to the magnetisation of the rod, a set of fairly accurate results can readily be obtained. If it be desired to discover exactly what the increased effect due to the iron core is at every stage, it is only necessary to remove the core, and take another set of readings with the coil alone, employing a similar set of values for the current strength; and then, deducting the

deflections so obtained from those previously obtained with the core in the coil, the effect due to the iron can be deduced. Or a second similar coil (without an iron core) might be placed on the other side of the needle, and the two coils being joined in series, so that they would always have equal currents flowing in them, the position of the subsidiary coil might be adjusted until its effect on the needle just balanced that of the first coil without its iron core. On then inserting the core any deflection obtained would be due to the increased effect caused by the presence of the iron.

Such results are best shown by plotting on squared paper curves similar to those given in fig. 115. This squared paper,

FIG. 115.



which is exceedingly useful, is usually ruled with a number of equidistant horizontal and vertical lines, the former being, however, omitted in the present instance. Let it be supposed that the line O D is divided into a number of equal parts, corresponding to the various current strengths, so that, for example, from O to the tenth division would represent five times the current strength that would be indicated by two such divisions. Let us also suppose that O M is divided equally, and that the divisions correspond to the various effects produced by the upper end of the iron rod and coil upon the needle. Let us now suppose currents of various

strengths, indicated by the distances along O D, to be sent through the coil, then any one effect which the coil with its core exerts upon the needle can be measured along the line O M, and the distance thus measured marked off upon the corresponding ordinate projected from O D. The thick upper curve O A drawn through the intersecting points shows graphically, by its distance from O D, the deflecting effect produced upon the needle by the various currents corresponding to the distances along O D. Let it be further supposed that, without in any way altering the position of the needle or of the coil, the core is withdrawn and the various currents again sent through the coil. Then the various magnetic effects of the coil upon the needle are clearly indicated by the 'curve' O B, which, in this case, is a straight line, and which demonstrates, therefore, that the field produced by the coil is proportional to the current flowing through it. The third curve O C is particularly interesting. Suppose the magnetic effect due to the coil alone, and represented by the distance D B, to be deducted from the joint effect produced with the same current by the core and coil combined, and represented by the distance D A, then the remainder B A = D C will represent the effect produced by the core alone. And if this subtracting process is carried out along each of the ordinates, the curve O C, which shows at every point the increased effect due to the iron core, will be produced. Now, it will be observed that, after a certain point has been reached, this curve becomes a nearly horizontal straight line, indicating that the saturation point of the iron has been reached, and that any further increase in the current strength does not add appreciably to the magnetisation of the core, the increase in the strength of the field developed being mainly that due to the coil itself. It is perhaps permissible to assume that the two curves O C, O B, would, if the experiments were carried far enough, intersect, at a point where the permeability of the air equals that of the saturated iron.

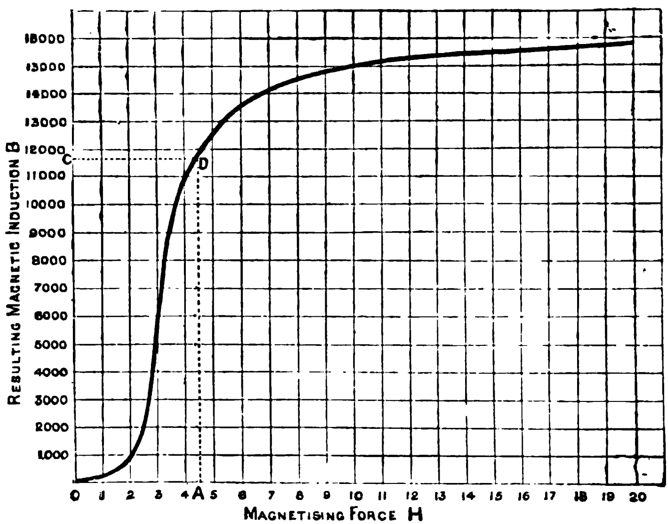
The following table gives a number of results obtained for a certain specimen of soft iron by Professor Ewing. The specimen took the form of a long thin rod, which was caused to deflect a small suspended needle or 'magnetometer' in a manner similar to that just described, and the results are perhaps more accurate

than those of earlier date from which the curve given in fig. 115 was drawn.

H	B	μ	H	B	μ
·32	40	120	5·17	12,680	2,450
·84	170	200	6·20	13,640	2,200
1·37	420	310	7·94	14,510	1,830
2·14	1,170	550	9·79	14,980	1,530
2·67	3,710	1,390	11·57	15,230	1,320
3·24	7,300	2,250	15·06	15,570	1,030
3·89	9,970	2,560	19·76	15,780	800
4·50	11,640	2,590	21·70	15,870	730

In fig. 116 these tabulated results are graphically shown by the curve in which the various values of the magnetising force **H**

FIG. 116.



are plotted as abscissæ, and those for the corresponding induction **B** as ordinates. One side of each square represents one unit of magnetising force, and another side one thousand units of magnetic induction. For example, it will be seen from the table that a magnetising force of 4·5 developed in the iron 11,640 lines of force per square centimetre, and this particular experiment gave

the point D on the curve. The position of this point was of course fixed by first taking the point A at 4·5 units distant from O, and then the point C at a distance corresponding to 11,640 units from O, and from these two points drawing lines at right angles to the horizontal and vertical base-lines respectively, these lines intersecting at the point D. The curve by its slow initial rise from the point O, followed by a sudden rise, clearly illustrates the fact that the permeability of the iron rapidly increases after a few lines of force have been projected through it, while the decided bend, after the point D has been passed, shows the stage at which the iron becomes saturated. It will also be observed that by increasing the magnetising force from 2 to 7, the magnetic induction was increased to the extent of about 13,000 lines; while at a later stage a twofold increase in the magnetising force, that is to say from 10 to 20, failed to increase the induction by 1,000 lines. This emphasises the fact that it is uneconomical to work an iron core above a certain density, and that a sufficient quantity of iron should be employed to prevent the saturation point being passed.

In addition to its high permeability, pure soft iron has another property which recommends its adoption for the cores of electro-magnets, and that is its low 'retentivity,' for in many cases electro-magnets are required to develop as strong a field as possible at some particular point directly the current commences to flow, and to lose or be deprived of all traces of magnetisation on the cessation of the current. Steel, as we have already seen, always retains a large proportion of the magnetisation imparted to it. Hard and impure iron have similar properties, inferior only to steel itself. There is no doubt that these properties of permeability and retentivity are very largely governed by the molecular structure of the iron or steel, and by the greater or less rigidity obtaining among the particles of the metal. In fact, the two properties to a great extent go together; for all qualities of iron or steel through which it is difficult to urge the lines of force, or to magnetise, are found to be correspondingly obdurate when it is sought to demagnetise them, or deprive them of magnetisation. There is, therefore, a double gain in employing pure soft iron, for not only is its permeability greater, but its retentivity is also less than that of impure or hard iron.

On the other hand, in selecting a material for permanent magnets, the principal thing to be considered is the retentivity, which, of course, should be as high as possible. No substance has yet been found which is, in this respect, superior to good hard steel. Some specimens of steel have been made so hard that efforts to appreciably magnetise them have proved futile. One of the most remarkable features to be observed in this matter is the extraordinary effect produced by the admixture of a small—one might almost say a minute—proportion of other, or foreign, substances with the iron. Just as a fractional proportion of iron or other metal added to copper causes a large increase in its electrical resistance, so the addition of carbon, tungsten, phosphorus, sulphur, arsenic, &c., to iron, reduces its permeability and also increases its retentivity. In the case of ordinary steel the retentivity is evidently due, in a great measure, to the presence of carbon, and, with a bar of good magnet-steel, the permeability is so feeble, and the retentivity so great, that it is impossible, by electro-magnetic induction, to upset the molecular arrangement in the interior of the bar, so that the magnetisation is in reality little more than skin-deep. This can be easily proved by magnetising a small piece of very hard steel and then immersing it in dilute sulphuric or hydrochloric acid. In a few moments the surface of the metal will have been dissolved, and on withdrawing it from the liquid all traces of magnetisation will have disappeared. Consequently, it is preferable, in making a large permanent magnet, to build up a number of thin strips of steel cut to size and then magnetised separately. On fastening them together, the built-up, or 'laminated,' magnet will be found capable of producing a far stronger field than can be obtained with any solid magnet of similar dimensions. It should, however, be added that in building up such a compound magnet there is no advantage in employing *brass* screws or bolts to fasten the individual magnets together as is usually done. In fact, this plan cannot but disperse the lines of force passing through the magnets, and therefore weaken, more or less, the polar strength. Iron screws or bolts are mechanically and magnetically preferable.

It is interesting to notice that specimens of steel have been made, containing 12 per cent. of manganese, which it has been

found practically impossible to magnetise even under the influence of a very powerful field. Apparently the molecular rigidity is so great that no ordinary magnetising force can overcome it and make the particles take up new positions ; and this assumption is partly borne out by the fact observed by Mr. Hadfield (who introduced this particular kind of steel) that long continued vibration appreciably increases its susceptibility to magnetisation. Similar results follow when the proportion of carbon, phosphorus, sulphur, &c., mixed with the iron exceeds a certain small limit, while the admixture of even a small percentage of antimony suffices, it is alleged, to destroy all trace of magnetic properties. There should certainly be a large field of practical utility open to the economical manufacture of unmagnetisable iron. For example, the bed-plates of dynamos are frequently separated from the field-magnets by huge slabs of zinc or brackets of gun-metal because, otherwise, the bed-plates would form what may be called a magnetic short-circuit between the poles of the field-magnets. Zinc is mechanically much weaker than iron, and this, added to its very much higher price, renders its use objectionable. Gun-metal, although much stronger than zinc, is still more expensive. To avoid the difficulty, comparatively small dynamos are rarely designed now with their pole pieces downwards, but are turned about so that the bed-plate is connected to the yokes or magnetically neutral portions of the field-magnets. Under such circumstances only a very few of the lines are wasted by passing through the bed-plate.

To ensure that the armature of an electro-magnet similar to that illustrated in fig. 113 shall be capable of transmitting a large percentage of the number of lines of force which pass through the core, it is evident that it must at least be equal in permeability and correspondingly massive. It should certainly be equal in section to the core.

It will be seen that the coil is divided into two sections, placed one on each limb or leg of the core. The winding is such that, were the core straightened out and the coils pushed together so that their ends meet, they would form one continuous coil or helix ; otherwise similar instead of dissimilar poles would be developed at the extremities of the core. The iron should preferably be the best and softest procurable, and should be bent so that the poles are

brought together; a comparatively large number of the lines of force will then pass through the space between the poles when the armature A is removed. The surfaces in contact should fit as truly as possible, so that there is the minimum air space between them. Sharp corners or edges should be avoided, and, since the natural shape of the lines of force is circular, the whole should approximate to the circular form, when there will be little tendency for the lines of force to 'leak out' of the iron and complete their circuit through the air space.

Such horse-shoe electro-magnets are frequently constructed to sustain a weight. The sustaining power is not, however, necessarily strictly proportional to the magnetising force, or even the total number of lines of force produced, as this power depends upon a number of secondary considerations (such as the shape of the pole pieces or extremities of the core, the dimensions and surface of the armature, and the method of applying the weight to be sustained), some of which do not require to be taken into account when estimating the electro-magnetic field itself. The weight can be suspended from a hook fixed to the middle of the armature, so that the pull upon the two poles is equal, the sustaining power being measured by the weight which can be supported by the armature without causing its separation from the magnet.

It is, however, frequently preferable, for convenience of construction, as in the case of most forms of dynamo-electric machines, as well as in telegraphic and other similar apparatus, to build up an electro-magnet in which two straight cores are yoked together by a piece of soft iron which is screwed or bolted to them. The yoke must naturally be massive, and the surfaces fit truly to avoid as far as possible the introduction of a magnetically resisting air space.

Reverting to the question of magnetic inertia, it may be mentioned that any cause which may operate to set up molecular vibrations in a piece of iron or steel facilitates either magnetisation or demagnetisation—that is to say, if the metal is placed in a magnetic field and vibrations then set up in it, it will be more readily and more powerfully magnetised than would be the case were the vibrations not set up, and, conversely, a magnet loses its magnetisation by being set in vibration, due to the fact that

facilities are thereby afforded for the individual particles, which are themselves magnets, to partially rotate and form little closed magnetic circuits in the mass of the metal. These vibrations can be caused by heating, hammering, twisting, or any other similar violent treatment. Hence, steel magnets should always be placed down gently, and never dropped or thrown down, otherwise the magnetisation will be more or less destroyed. A magnet raised to a red-heat loses its magnetisation entirely, and this can easily be demonstrated by heating a magnetised sewing needle in a gas flame ; and, further, while at that temperature it is no longer attracted by a magnet, acting similarly to a non-magnetic metal. It recovers its magnetic properties on cooling down, but does not, of course, recover any magnetisation which may previously have been imparted to it.

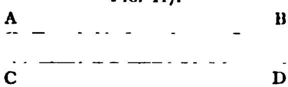
By adopting the precautions referred to, magnets can be made capable of sustaining more than thirty times their own weight, and a description of the method practically adopted for the manufacture of permanent steel magnets capable for some years of supporting about twenty-five times their own weight may prove serviceable. In this case, the best tungsten steel is employed. It is heated gently to a dull red heat and hammered into the required shape, care being taken not to raise the temperature too high, or the tungsten will be volatilised. A small magnet may therefore require to be placed in the fire several times before the necessary shape has been obtained. This process being completed, the steel is then hardened by being first placed in a close fire out of contact with air, so as to ensure uniform heating and to prevent the formation of a hard scale of iron oxide. It is then dipped into a water bath. This latter process must be carefully attended to, or the metal will be twisted or otherwise distorted. It should be held vertically, and, if of the horse-shoe pattern, its extremities should be dipped in first, and then steadily lowered into the water. The next process is that of polishing, after which it is passed a few times over the poles of a large and powerful permanent magnet, the steel being turned over once or twice so as to magnetise both faces. Of course, a large electro-magnet, with a powerful current circulating through its coils, can be employed, but the permanent magnet is quite as efficient provided it be sufficiently powerful.

Concerning the difficulty of magnetising very hard steel to any great depth below the surface, it may be interesting to mention briefly some experiments which we have performed, using sulphuric acid solution to dissolve the surface particles of the steel. Our experiments were suggested by the publication by Prof. Hughes of his classical papers, which did more to throw light on the fundamental principles of magnetism, and constituted a greater advance in the practical application of the science, than any other set of experiments or publications either before or since. One of the most beautiful experiments was that in which a steel rod, or, better still, a steel strip, was slightly twisted to the right and then magnetised by being passed over the pole of a bar magnet in one direction. It was then similarly twisted to the left and oppositely magnetised by being passed over the same pole in the reverse direction. Hughes found that when the torsion was released, and the strip assumed its normal condition, it gave no evidence of magnetisation, but by simply twisting it either to the right or to the left it at once gave evidence of magnetisation, and in the same sense as that imparted to it while under the particular twist—that is to say, the polarity could be reversed by twisting first to the right and then to the left. In our experiments we sought to bring about this superimposed polarity without mechanically altering, by twisting or otherwise, the position of the particles of steel, and to demonstrate the success of the experiment by chemical means. For example, a small steel rod was raised to a red heat and plunged in water while in a strong magnetic field. It thus became hardened and at the same time powerfully magnetised throughout. It was next drawn gently over one pole of a powerful magnet in such a direction as to magnetise it in the opposite sense to that previously imparted, the process being continued until there was no external evidence of magnetisation. The rod was then immersed in a sulphuric acid solution, in line with a magnetometer. Immediately after immersion there was no deflection of the magnetometer needle, the rod behaving similarly to a piece of unmagnetised steel. In a very short time, however, the magnetometer needle began to move slowly, say, to the left, the deflection gradually increasing up to a certain maximum from which it as gradually fell to zero, when it was found that nearly the whole of the steel rod had been

dissolved. Were the process to which the steel rod had been subjected unknown, it would appear that the mere immersion in the solution and the consequent chemical action had imparted magnetisation to it; but, of course, the fact is that the outer layers only were reversed in magnetisation, and to a sufficient extent to just neutralise the magnetisation of the interior of the rod, which remained unaltered. As the outer layers were dissolved, the interior magnetisation preponderated more and more, until when the whole of the exterior magnetised shell had been dissolved the maximum deflection was obtained. The subsequent fall in the deflection resulted from the gradual dissolution of the interior portion. A number of other experiments were performed, some of them of a more or less fanciful character, but all involving the same principle.

We have stated frequently—so frequently, in fact, that we feel it almost necessary to apologise for repeating the statement—that when a current of electricity is set up in a wire, an electro-magnetic field is almost immediately generated in the region surrounding that wire. But the converse of this is also true—viz. that when an electro-magnetic field is suddenly set up around a wire, there is a tendency for a current to be generated in that wire *during the setting up of the field*, and if the wire forms part of a complete circuit a current will flow along it. The source of the field is immaterial: it may be a permanent magnet, a straight wire, or a helix carrying a current; all that is essential being that the lines of force should be thrust across the wire, or that the wire should be moved in such a manner as to cut the lines of force *transversely*. As an instance, let A B, C D (fig. 117) be two wires running side by side for a certain distance, each forming part of a complete circuit. If a current is started in A B, lines of force will immediately start from its centre, or axis, in the form of widening circles, and, cutting the second wire, C D, set up an electro-motive force therein and, in consequence, generate an electric current. It is only, however, while the lines of force are actually cutting the second wire that the E.M.F. is developed, and as this cutting ceases immediately the current in A B arrives at its full strength,

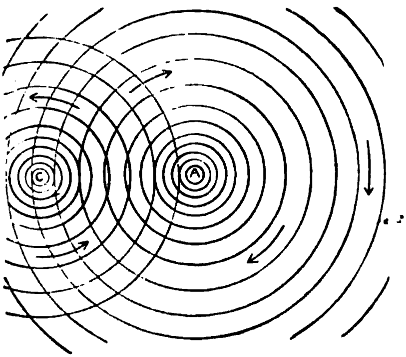
Fig. 117.



the induced current lasts but for a moment. In direction it is opposite to the current in the wire A B. While the original current is steady many of the lines of force due to it are embracing the adjacent wire C D, but, being relatively at rest, they have no effect thereon.

When the current in A B is stopped, all the lines of force collapse upon it, and those which extended beyond the wire C D again cut it, and thereby induce in it another momentary current. But, since the lines now cut the wire C D in the opposite sense (for they approach it from the opposite side), the resulting current is in the opposite direction to the previous one—that is, it is now in the same direction as the inducing current which was flowing in the wire A B. By noting the direction of the lines of force due to the inducing current, and the direction in which they must coil round the wire C D during the time they are passing it, we might predict the *direction* of the induced current in either case. It is somewhat difficult to make this clear by diagrams, but an analogy may assist us to a great extent.

FIG. 118.

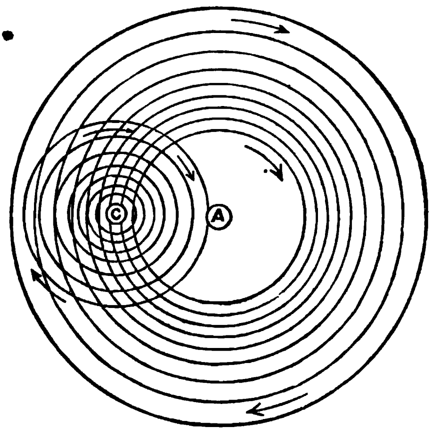


When any small body is dropped on the surface of still water it breaks that surface into a series of ripples which take the form of ever-widening concentric circles as in fig. 118, where A is the point of generation. In such a manner do the lines of force spring into existence from a wire, only with far greater rapidity, and it is difficult in either case to fix a limit to their extent if the medium (the water or the ether) is not limited.

Now, if these water ripples meet any obstruction, for instance, a post at the point C, they set up around it a series of circular ripples, feebler, perhaps, but precisely similar in character to themselves. It is difficult at present to say with certainty exactly what happens in the case of the electro-magnetic lines of force,

but we can safely use the analogy for the purpose of demonstrating that the direction of the lines of force round the wire in which the current is induced is opposite to their direction round the inducing wire. For, suppose, as in the case of the lines of force, the original ripples round A to have what is called a positive direction—that is to say, that they circulate in a right-handed direction after the manner of the hands of a clock, as indicated by the arrows; then, since that direction would not be altered by reflection at the obstacle C, they must go round C left-handedly or contrary clock-wise. Now, if these were electro-magnetic lines of force we know (page 86) that their direction would indicate a current flowing *downward* through A, and *upward* through C, and thus we can readily perceive how the starting of a current in one wire gives rise to an *inverse* one in a neighbouring wire. Further, we see that it is only while the original ripples generated from A are *passing* the point C that these secondary ripples can be generated or called into existence, and we may again picture to ourselves how it is that a current is induced in a wire, only during the time that the current in the neighbouring wire is attaining its full strength.

FIG. 119.



Let us now suppose it possible to cause a series of ripples to collapse upon the point A, in the same manner as we imagine lines of force to collapse upon a wire. Before arriving at A they would meet with C, and, as before, generate a series of secondary ripples, but in this case their direction round C and A would be the same, for now they approach C from the opposite side. Again assuming the ripples to have a positive direction, the arrows in fig. 119 show that their direction will be

the same round each, and if A and C were wires and the circles lines of force, the current in each wire would be flowing downward through the paper. It thus becomes easy to imagine how the stoppage of a current in a wire induces in a neighbouring wire a current in the *same* direction as itself. The wire in which a current is induced is called the secondary, and the one which carries the inducing current is termed the primary wire.

Now, if in fig. 117 the wire A B, while carrying a steady current, were suddenly brought close to C D, or if C D were suddenly brought close to A B, the lines of force would cut C D in precisely the same manner as they did when a current was started in A B. The result would therefore be the same, that is, a momentary current would be developed by induction in C D, in the opposite direction to that of the current in A B. Furthermore, if the two wires were then suddenly moved asunder, C D would be cut by the retreating lines of force, just as it was cut during the stopping or the dying away of the primary current, and a direct induced current would therefore be the result.

These induced currents bear a very simple ratio to the currents producing them. The E.M.F. in the secondary wire is proportional to the number of lines of force which cut it, and also to the rate at which they cut it. Now, the number of lines of force may be increased by increasing the strength of the current in the primary wire, or by adding to the length of the wires in proximity. It is, however, more convenient to wind the longer wires in spirals or helices, when the effect will be similar to that which would result from two long straight wires. It is evident that the two wires should be as close together as possible, otherwise those lines of force very near the primary wire would not reach the secondary wire at all, and would, therefore, fail to produce any effect therein. In some cases when it is desired to obtain a powerful induced current, the primary and secondary wires are wound in the form of concentric helices, and an iron core is inserted to increase the number of lines of force which cut the secondary. Having by such means made the number of effective lines as high as possible, the only other thing to be done in order to increase the secondary E.M.F. is to make the rate at which the secondary is cut by these lines as great as possible.

Now, supposing the two wires A B, C D (fig. 117) to lie quite close together, and the current in A B to be started and to arrive at its full strength instantaneously; the rate at which its lines of force cut C D would then be a maximum, and it would not be possible to further increase the E.M.F. of the induced current, except by increasing the strength of the current in A B and so increasing the *number* of the lines of force. But in practice a current does not rise to its full strength instantaneously, nor does it stop suddenly; time is taken for the lines of force to spring into existence and to die away, and under certain conditions this time may be considerable. To understand the principal cause of this sluggishness, let us refer again to fig. 118 and further study the case of the water ripples. A little thought or experiment will make it evident that the secondary ripples round C will quickly reach the point A, and if the body which caused the disturbance is still there, will set up around it ripples in the same sense as the original ones. Now, suppose two wooden balls, A and B, were dropped into the water at the same moment close together and equidistant from C, they would set up ripples round C, each to the same extent and in the same sense; in fact, the number round C would be doubled. But still stronger is the effect of A and B round each other, and (still assuming a positive direction just as we do for lines of force) the direction of the ripples so set up round each will be opposite to those which it generates. In the same way if a primary wire is looped into two convolutions, A and B, they will generate round an equidistant loop of the secondary C just double the number of lines of force which one will; but they also react upon each other, each setting up round the other, lines of force which would generate a current tending to stop the primary one, the result being that this primary current does not rise so rapidly to its full strength. This retardation increases as we increase the number of convolutions; in fact, it varies directly as the square of the number of convolutions, because each one acts upon all the others and they in their turn act upon it. Therefore the retardation in a coil of 100 turns would be 100 times as great as in a coil of 10 turns.

In a precisely similar manner the reaction of adjacent convolutions prevents the instantaneous *stoppage* of a current; for, at

the moment of disconnecting the battery or other current-generator, lines of force collapse upon each convolution, and in so doing they cut the other convolutions and generate a direct induced current which will also vary as the square of the number of turns, and tend to prolong, or retard the disappearance of, the primary current.

The electro-motive force resulting from this collapsing of the lines of force may be, and usually is, much higher than that which maintains the original current. For, supposing the battery used consists of ten Daniell cells, then if the poles are connected by a short piece of wire, no spark, or, at the most, a very feeble one, is observable when the circuit is closed and opened quickly. If this same battery is made to send a current through a coil of many turns of wire, although its resistance may be high and cause the current to be comparatively weak, yet, on breaking the circuit, a spark will be observed. This is due to the fact that the lines of force fall back so quickly upon their respective convolutions in the coil, that they cut the adjacent convolutions with sufficient rapidity to generate a momentary E.M.F. high enough to produce a current sufficiently strong to volatilise a portion of the metal, and to maintain the current across the vapour-filled space for a brief interval, even after the wires are moved asunder. This effect is even more striking if in a dark room contact is broken between a wire and a mercury surface, when a little of the mercury is volatilised; and, since the effect of iron placed in the vicinity is to increase the number of lines of force which are active, the spark can be increased enormously by placing a core inside the coil.

The term 'self-induction' has been given to this action, which prevents the instantaneous rise and fall of a current, and it will be evident, from what has been said, that, in the case of a simple straight wire, this phenomenon is almost imperceptible, and that, in order to make the self-induction of any circuit a maximum, the wire should be wound into as many convolutions as possible, and be provided with plenty of iron.

In some cases it is desired to design electro-magnets which shall be affected as little as possible by brief, sudden fluctuations of the magnetising current. It is manifest that in such a case the electro-magnetic inertia—that is, the self-induction · must be made

high by using a long and massive core and a great number of turns of wire; for, as we have seen, self-induction prevents a rapid rise or fall of the current, in just the same way that the inertia of matter prevents any instantaneous change in its motion. If, on the other hand, an electro-magnet is required to be quick-acting, or to be very sensitive to any variation in the current, self-induction should be as low as possible, and, in order to obtain this, the coil should consist of as few turns of wire as possible, and the core should be short, and not form a complete circuit of iron.

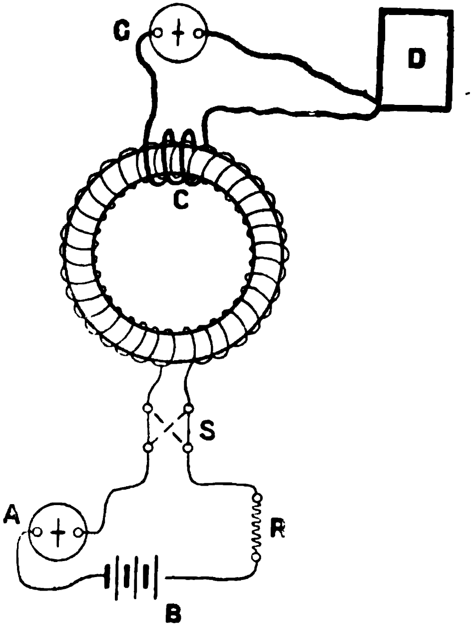
The fact that when a conductor is cut by lines of force a current is generated therein if it forms part of a complete electrical circuit enables us to compare the strength of different fields. For example, we can place a small exploring coil which encloses just one square centimetre in a certain field with its plane at right angles to the lines of force, when it will enclose lines of force equal to B, or the number per square centimetre in the field. By suddenly removing the coil from the field it will cut all the lines of force which it previously embraced, and the resulting current will be proportional to this number. Consequently, if the coil be similarly placed in, and removed with equal suddenness from, a second field, the second current so obtained will also be proportional to the strength of that field, and by comparing the strength of the two currents we can effect a comparison between the strength of the two fields. Instead of removing the coil it may be suddenly turned through a right angle, when its plane will lie parallel to the lines of force, in which position it will embrace none of them; or it may be turned through 180 degrees, in which case twice the current strength will be obtained on each occasion, since the coil will cut the whole of the lines of force which it embraced, twice instead of once only. The resistance of the electrical circuit and all other conditions must of course remain the same during the experiments on both fields. To put the matter more precisely, the electro-motive force generated in the coil will be proportional to the number of convolutions in the coil, to the number of lines of force which it cuts, and to the speed at which it cuts them; while the strength of the resulting current will be proportional to this electro-motive force, and inversely proportional to the resistance in the circuit.

Again, instead of moving the coil, the lines of force may be suddenly removed from it, or, better still, they may be reversed; and this latter method is perhaps the best of all for measuring the value of the induction in a sample of iron with various magnetising forces. The iron is preferably made in the form of a continuous ring, and overwound evenly with a coil through which a current may be sent and reversed; and the current strength and number of convolutions per centimetre n being known, the value of the magnetising force may be calculated from the formula $\mathsf{H} = \frac{4\pi \text{C} \times n}{10}$, where C is the current strength in amperes. If the iron is homogeneous, the magnetic induction **B** will be the same in every portion of it, and a small coil wound over the iron at any point will embrace all the lines passing through the iron. Then by reversing the current the iron is suddenly demagnetised and magnetised in the reverse direction, and all the lines of force so made to vanish and start in the opposite direction must cut the little coil and generate a current therein.

In fig. 120 we show a simple arrangement of apparatus suitable for experimenting by this method, which has been used by a number of investigators. In the primary circuit is placed a battery B, a resistance coil R for varying the current strength, and a galvanometer or ammeter A for measuring the current, all being joined in series with the magnetising coil which is wound uniformly all round the iron ring. The switch S enables the current to be started, stopped, or reversed in direction. The secondary circuit consists of the small coil C, a galvanometer G, and a coil wound on a rather large wooden frame D. G is preferably a 'ballistic' galvanometer, having a somewhat massive needle suspended by a silk fibre, it being essential that the whole of the transient induced current shall flash through the coils before the needle has moved appreciably from the zero position. Under such conditions the deflection of the needle will be proportional to the total quantity of electricity flashed through the coil, independently of a small variation in the time occupied in passing on different occasions, since the needle receives the whole of the impulse while in the most sensitive position. A mirror attached to the needle enables the deflections to be read by the movements

of a spot of light, as previously explained. The coil on the frame D, which is permanently connected in circuit, enables the galvanometer to be standardised. When laid flat on a table it embraces a known number of lines of force due to the earth's magnetism (the area of the coil and the vertical component of the earth's magnetism being known), and if turned suddenly over it will cut all these lines twice, and the deflection caused by the result-

FIG. 120.



ing current being thus due to an inductive effect of known value, all other deflections can be compared with it. The small coil C should preferably be wound next the iron, otherwise it may embrace a considerable space containing air, copper wire, &c., and many lines of force will pass through this space and be embraced by and cut the secondary coil, especially when the iron has its permeability greatly reduced by being strongly magnetised.

By means of such a set of apparatus, it is possible to study the

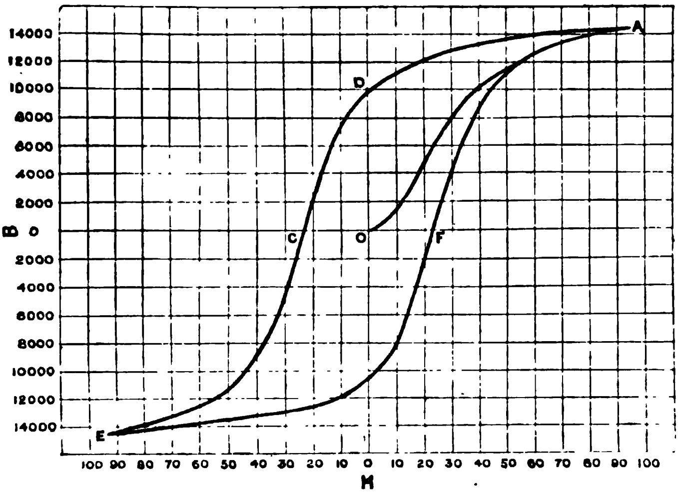
manner in which the magnetising force, magnetic induction, and permeability, vary in the case of any sample of iron or steel, and the results can conveniently be plotted in curves, which for soft iron would be approximately similar to that given in fig. 116. For hard iron, cast iron, or steel the curve would rise with a gentler slope, and not attain such a final height if plotted to the same scale.

In such a case as that of the field-magnet core of a dynamo machine, where the core is constantly magnetised in one direction only, permeability is practically the only quality of the iron which need be taken into account. But another quality of even greater importance has to be considered with respect to an iron core (such as an armature core), where the magnetisation is repeatedly and rapidly reversed, for this reversal, involving as it does the changing of positions of the particles of the iron, cannot be effected without an appreciable expenditure of energy, which is converted into heat. The name 'hysteresis' has been given to that property of the iron in virtue of which a definite amount of energy has to be expended in order to change the position of its particles, and the energy so expended varies with the intensity of the magnetisation, the mass of the iron, the rigidity with which the particles are set in position, and the rapidity with which the reversal is effected.

In fig. 121 we give a curve which will serve to illustrate this phenomenon, and which is based upon the experiments of Professor Ewing. It was obtained by experimenting upon a specimen of annealed pianoforte steel wire, and plotting the various values for the magnetising force **H**, and the resulting magnetic induction **B**. The first part of the curve, starting at O and ending at A, rises similarly to that shown in fig. 116. It will be observed that when **H** was no less than about ninety-five units, the number of lines urged through the specimen barely exceeded 14,000 per square centimetre. When the point A had been reached the magnetising force was reduced step by step and the induction remaining at every step observed. The curve from A to C was thus obtained. If no energy were expended in the process of turning the particles into new positions, this descending curve would coincide with the ascending one; but it will be observed that it lies considerably to the left of it, and as indicated by the ordinate O D, no less than

10,000 lines per square centimetre remained in the steel when the magnetising force **H** was reduced to zero. The length of this ordinate O D gives a measure of the retentivity of the steel. In order to demagnetise the specimen it was necessary to apply a negative magnetising force (by reversing the direction of the current), and complete demagnetisation was effected when $\mathbf{H} = -23$ approximately, as indicated by the length of the line O C. Dr. Hopkinson has happily applied the term 'coercive force' to the force (as measured by O C) which it is necessary to apply

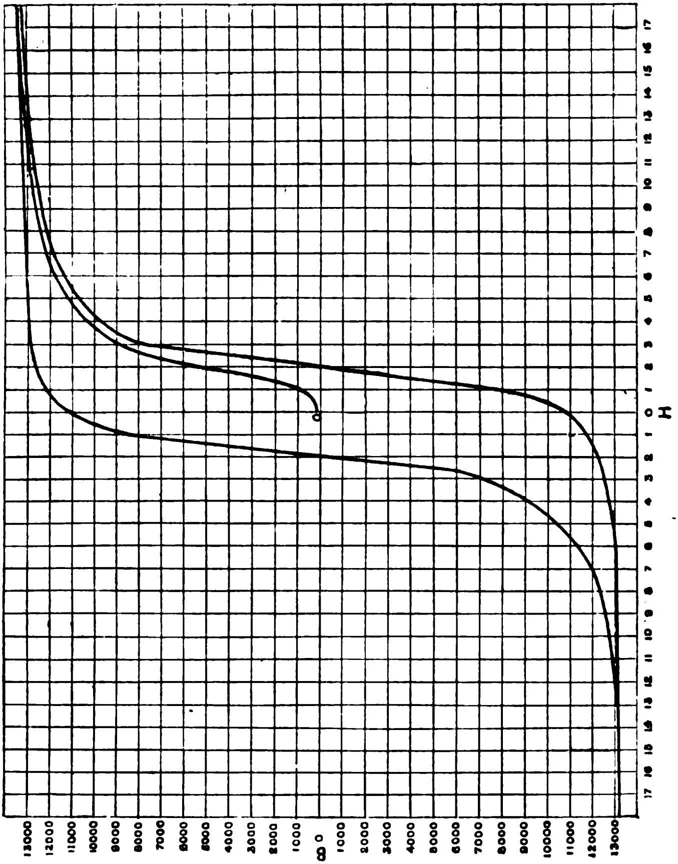
FIG. 121.



in order to demagnetise any specimen after it has been magnetised to any given degree, and this coercive force can be definitely indicated in terms of **H**. From this point where $\mathbf{B} = 0$ the negative magnetising force was increased until it had the same value as was previously given to it in the positive direction, when the value of **B** was the same as on that occasion, but negative instead of positive. From this point E the magnetising force was diminished step by step, then reversed and increased positively as before, thus giving the ascending curve E F A. It will be evident that the area E C A F enclosed by the outer curves will for

any given case become greater as either the maximum induction reached, or the coercive force of the specimen, is increased;

FIG. 122.



and it has been shown that for any specimen the energy in ergs wasted in the complete cycle of operations, by means of which the curves E C A, A F E are obtained, is proportional to the area of the figure enclosed by those curves. If the curve be plotted to an appropriate scale, the area enclosed divided by 4π gives the

number of ergs per cubic centimetre of iron wasted during one complete cycle; that is to say, in changing the magnetisation of the iron from its positive maximum to its negative maximum, and then carrying it back again to its positive maximum. As an instance of the effect of hardening, it may be mentioned that a similar specimen of pianoforte steel wire, when made very hard, had a coercive force of over 40 units, which value would greatly increase the area enclosed by the curves and correspondingly increase the hysteresis loss.

It will be seen that the coercive force, which depends chiefly upon the nature of the material employed, is the principal factor in determining the amount of the energy lost by hysteresis, and hence the importance of selecting a material in which the coercive force has a low value, for use in those cases where the magnetisation is repeatedly reversed. As might be expected, the coercive force of soft iron is much lower than that of steel or hard iron, and this will be evident from an inspection of fig. 122, which is also based upon Professor Ewing's experiments. It should be noted that in order to obtain a clearer figure the magnetising forces are plotted to a much greater scale than those in fig. 121, so that the two areas must not be directly compared. The value of the coercive force did not in this case exceed 2 units.

Both of these hysteresis curves were obtained by experimenting with a ballastic galvanometer after the method illustrated in fig. 120, the only difference being that the specimens were in the form of long straight wires instead of rings, with the coils wound over the middle portion of the wire.

It is interesting to note that the soft iron specimen possessed a little remanent magnetism, so that the initial curve in fig. 122 does not start exactly at zero, but a short distance above it.

CHAPTER VIII.

DYNAMO-ELECTRIC MACHINES (ALTERNATE CURRENT)

IN the preceding chapters we have dealt with some of the principal laws of electric currents, and the most striking phenomena connected with them. The student will not have failed to notice two important facts: (1) That when a wire through which a current is passing in placed in a certain position in any electro-magnetic field, it has impressed upon it a definite mechanical force tending to move it into another part or out of the field; and (2) when a conductor is mechanically moved in a field transversely to the lines of force traversing that field, a certain electro-motive force is determined, which sets up a current in the wire if its two ends are connected. Extensive use is made of both these effects in practice, and on a very large scale. Machines which are constructed to transform energy which exists in the form of electric currents into energy in the form of mechanical motion, and, conversely, machines which are able to transform energy in the form of mechanical motion into energy in the form of electric currents, can be included under the generic head of 'dynamo-electric machinery.'

We shall first consider machines of the latter class, which are commonly known by the shorter name of 'dynamos,' deferring a consideration of the other class until an opportunity offers for dealing with such apparatus under the more generally adopted title of 'motors.'

In every machine for the conversion of energy, there is always a certain amount of loss attending the conversion; in other words, less energy appears in the new than existed in the original form.

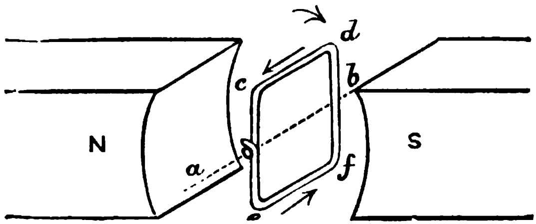
The more perfect the machine, the less does this loss become, so that a theoretically perfect machine would be one in which there is actually no loss at all. It is absolutely impossible to construct such a machine, but in every case the chief aim of the engineer should be to make the loss as small as possible, or to make the machine as 'efficient' as possible. The proper way of doing this is to start with the fact established in accordance with the doctrine of the 'conservation of energy,' that energy can never pass out of existence or be destroyed; that, therefore, the whole of the energy put into the machine reappears in some shape or form, although only a part appears in the exact state in which it is desired. Steps should then be taken to ascertain exactly what form the other or undesired part takes, and the designer of the machine should study how to reduce that same part, which may be called 'waste,' to a minimum. In all machines which have moving parts, a certain percentage of the energy takes the form of heat, due to friction at the bearings and other surfaces which come into contact. Every dynamo has moving parts, and is therefore subject to loss from this cause, and the well-known methods of reducing friction by good workmanship and design, and the judicious use of oil or other lubricant, are taken advantage of to minimise the loss. But there are many other causes besides mechanical friction which operate to reduce the efficiency of a dynamo; they are mainly due to electro-magnetic phenomena, and careful study is required in discovering how to eliminate or minimise them, although in some instances the loss may be readily localised, because, like friction, these phenomena convert a certain amount of the original energy of mechanical motion into heat. One of the principal features, then, by which a dynamo is judged is its efficiency, or by the ratio of the energy re-appearing as electric currents to the total amount given mechanically to the machine.

We will start with the consideration of the simplest type of dynamo-electric machine, and, observing its weak points, endeavour to trace its development into a practical and highly efficient piece of apparatus.

Now, it is only during the time that the lines of force of a field are being cut by a conductor that an electro-motive force is induced in that conductor; therefore, in order to obtain a continuous

current, or a very rapid succession of currents, it is evident that either the conductor or the field must be kept continually in motion. Let us first study the case of a fixed field and a moving wire, assuming, for the moment, that we have a strong and fairly uniform field, produced by the opposite poles of two large permanent bar-magnets placed near to each other, or by any other convenient means. A uniform field has been already defined to be one in which the lines of force are straight, parallel, and equidistant. It is not easy to obtain a strong uniform field of any great extent, so that the most convenient way of continually cutting lines of force is to cause the conductor to move in a circular path, within the limits of a powerful field of comparatively small area. For instance, if the wire is bent into a single rectangular coil, as shown in fig. 123, it may be placed in the field with its plane at right

FIG. 123.



angles to the direction of the lines of force, so that as many as possible of these lines are made to pass through it. If, now, this coil is turned suddenly through an angle of 90° about the axis *a b*, its plane lies parallel to the lines of force, and it is obvious that none of them now pass through the coil. In the act of turning, both the top and the bottom limbs, *c d* and *e f*, cut a certain number of lines, setting up thereby an electro-motive force in the wire; but as these two horizontal limbs of the rectangle cut the lines from opposite sides, the direction of the resulting currents in them is opposite. In the lower limb, *e f*, the direction is, during the quarter of a revolution from the position illustrated, from front to back, and in the upper one, *c d*, from back to front. Both currents, therefore, pass round the coil in the same direction. The side limbs of the rectangle—that is, *c e* and *d f*—simply slide, or

slip, through the lines of force, and do not *cut* them; they, therefore, have no current induced in them, and, while adding to the resistance of the loop, are useless, except for the purpose of completing the electrical circuit. The student may now, with advantage, again read the paragraph on page 242 which indicates how the direction of an induced current can in every case be predicted. In the present case the lines of force pass from left to right, and the number cut by each limb, so far, is half the total number originally passing through the rectangle.

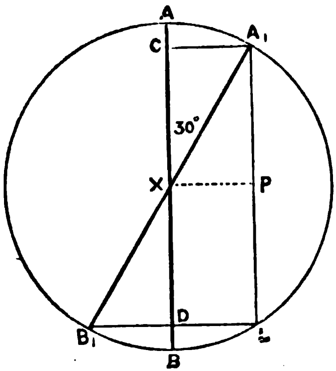
When the rectangle is turned through another 90°, so that the limb which was at first uppermost is now at the bottom, it has the maximum number of lines of force suddenly thrust through it again; another induced current is the result of this second quarter of a revolution, and as, during the movement, both the horizontal limbs cut the lines from the same side as they did in the first movement—that is to say, the one limb still cuts downwards and the other still cuts upwards—the direction of the current is the same as that developed during the first quarter of a revolution. Further, as the number of lines of force cut is in each case the same, the induced E.M.F. is also the same for each similar position, provided the rates of moving are equal.

If, therefore, the rectangle is rapidly turned at one sweep from its original position in fig. 123 through 180°, a current will be induced, in the direction shown by the arrows, during the whole of that movement. If the rotation is continued, on passing the 180° the horizontal limbs again begin to cut the lines of force, but they then cut them from their opposite sides, or in the opposite direction to that during the first half revolution. The resulting current is therefore in the opposite direction to the previous one, but of precisely the same strength at corresponding points if the motion is uniform. A continuous rapid rotation of the rectangle, then, will give rise to a series of currents alternating in direction, two distinct currents being generated during each complete revolution, the reversal taking place every time the rectangle passes the points at which its plane is at right angles to the lines of force—that is to say, those positions in which it embraces the maximum number of lines of force.

Supposing both the field and the speed of rotation to be

uniform, the question arises whether the E.M.F. is also uniform during, say, the whole time of a half revolution. As the induced E.M.F. is proportional to the *rate* at which the lines of force are cut, it is only necessary, in order to decide this question, to ascertain whether the rate of cutting is, under the circumstances, also uniform. A little reflection will show that just when the rectangle begins to move from its position in fig. 123 it is *cutting* hardly any lines at all, but that its horizontal limbs, like the vertical limbs, are rather sliding along or slipping through them, and therefore at the beginning of the movement the rate of cutting, and consequently the E.M.F., is comparatively low. But when the rectangle has turned through about 90°, it is cutting the lines almost at right angles; there is practically no sliding whatever, and the rate of cutting, and therefore also the E.M.F. produced, is much greater—it is, in fact, at its maximum. This gradually decreases until, when near the 180°, the E.M.F. is again at a minimum, and the reversal takes place.

FIG. 124.



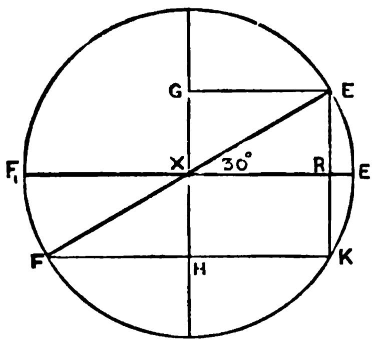
A reference to fig. 124 will make this clearer. A B represents the coil viewed end on in the vertical position; X the axis o rotation, and A_1 B_1 the position of the coil after it has been turned through 30°. Clearly the number of lines cut by the top limb of the coil are those enclosed in the space A C, and by the bottom limb those in the equal space B D. Therefore the total number cut during this movement of the coil through an angle of 30° from zero may be represented by the sum of these two lines A C + B D.

Now in fig. 125, E F represents the position of the coil after it has been turned through 60°; if from this point it rotates through another 30° its position is represented by E_1 F_1, and the lines of force cut during this movement embrace all those included in the space E K. Now E K is considerably greater than A C + B D, and therefore, as the field is uniform, the coil cuts a much greater

number of lines of force by moving through 30° when its plane is nearly parallel to the direction of the lines, than it does by moving through an equal angle while it is nearly perpendicular to them. But as the speed of rotation is uniform, it takes precisely the same time to pass through these equal angles, therefore the rate of cutting, and consequently the E.M.F., must be much greater in the former than in the latter case. In fact, the rate at any moment is proportional to the *sine* of the angle through which the coil has then moved from the vertical position.

We have defined a magnetic field of unit strength to be one having one C.G.S. line of force per square centimetre, and if a conductor one centimetre in length is moved transversely through this field at a velocity of one centimetre per second, it will cut one line of force per second, and thereby develop one C.G.S. unit of electromotive force. If the strength of field, the velocity, or the length of wire be doubled, the resulting E.M.F. will be doubled, the number of lines cut per second being increased twofold. If, however, we simply know the number of lines of force cut per second, the E.M.F. can be calculated without any consideration as to the length of conductor or as to strength of field.

FIG. 125.



If the field is not uniform, or if the wire moves at a varying speed, the rate of cutting, and therefore the E.M.F., will fluctuate. But the *average* of this fluctuating E.M.F. will be equal to the average rate of cutting, that is to say, it can be found by dividing the whole number of lines cut by a conductor by the time in seconds occupied in the cutting. If, therefore, the rectangle in fig. 123 makes one revolution per second, and the maximum number of lines of force embraced by it in the zero position is denoted by N, then each limb will cut 2 N lines per second, because it cuts every line during the downward sweep, and again

during the upward movement. Consequently each limb develops an average E.M.F. of 2 N C.G.S. units, and as both limbs are connected in series the total E.M.F. becomes 4 N units. Further, if the rectangle makes n revolutions per second instead of only one, then n times as many lines will be cut per second, and the average E.M.F. will be 4 N n units. But since the C.G.S. unit of electromotive force is so very small, a much greater practical unit, called the volt, equal to 100,000,000 C.G.S. units, is employed. All results obtained in C.G.S. measure must, therefore, be divided by this number to give the value in volts, and the simple equation may be written,

$$\text{average E.M.F.} = \frac{4\,\text{N}\,n}{100{,}000{,}000}\ \text{volts.}$$

It may be mentioned that the value of N is, in actual machines, very high, being, as a rule, several millions.

In practice, it is this average E.M.F. which in such a case concerns us most; but we may observe that if the rectangle were rotated at a constant speed in a uniform field, the actual E.M.F. being developed at any moment when it had moved through an angle a from the zero position would be

$$\text{E} = \frac{2\,\pi \sin a\,\text{N}\,n}{100{,}000{,}000}\ \text{volts.}$$

The above refers to the case of two active wires, forming limbs of a rectangle and joined up in series in a manner such as that illustrated in fig. 123, when the E.M.F. of one is added to that of the other. The resulting E.M.F. is, as we have already seen, twice that developed by one active limb; and if the wire were wound in a number of convolutions, it would be necessary to multiply by the number of active limbs then joined in series (instead of by 2, as in the present case) to obtain the total E.M.F.

The function above referred to as the 'sine' is one with which the student will frequently come in contact. Perhaps, therefore, it will now be as well to explain briefly what is meant by the sine of an angle. If in one of the two straight lines which contain any angle, such as E X R in fig. 125, any point, say E, is taken, and from it a line E R is drawn perpendicular to the other line, a

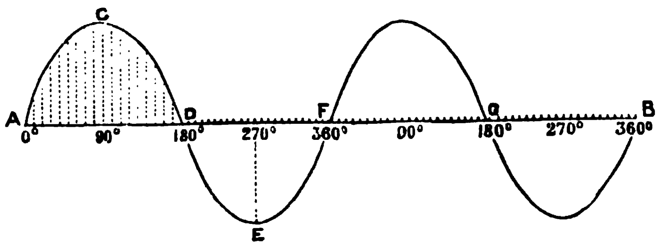
right-angled triangle, E X R, is formed. The length of the perpendicular E R divided by the length of the hypotenuse E X, that is, $\frac{E\,R}{E\,X}$, is a definite value, no matter what the area of the right-angled triangle may be, provided only that the angle E X R is unaltered. And this ratio $\frac{E\,R}{E\,X}$ is called the sine of the angle E X R. The sine of any other angle is similarly measured; for instance, in fig. 124 $\frac{A_1\,P}{A_1\,X}$ is the sine of the angle A_1 X P. Again, in the same figure, $\frac{A_1\,C}{A_1\,X}$ is the sine of the angle A_1 X C, and in fig. 125, $\frac{E\,G}{E\,X}$ is the sine of the angle E X G. If we always choose the same length of line for the denominator, as will be the case if it forms the radius of the same or equal circles, as E X and A_1 X, and consider it to be equal to unity, then the sine is simply measured by the numerator E R or A_1 P, that is, by the length of the perpendicular. When the angle becomes very small, the perpendicular, and therefore the value of the sine also, becomes very small; in the case of the imaginary angle 0° the perpendicular disappears, and the sine of 0° is then 0. When the angle is 90° the perpendicular coincides with and is equal to the radius. The sine of 90° is therefore 1, and this is the highest possible value of the sine. It decreases as the angle further increases, until, at 180°, its value is again 0. From here it is reckoned as negative, the sine of 270° being − 1. By referring to a table such as that on p. 100 the value of the sine of any angle can readily be found, and we can, therefore, calculate the relative value of the E.M.F. at any position of the rectangle, and also show diagramatically how the E.M.F. should rise and fall in a perfectly uniform field.

In fig. 126 the portion A F of the horizontal line AB represents a circle straightened out, each of the four equal parts into which it (A F) is divided being equivalent to 90°—that is, a quarter of a revolution of the rectangle. Similarly, this line A F might be subdivided into 360 parts to represent the 360 degrees, and any point along it could then be taken to denote the position of the rectangle when turned through a corresponding angle from zero. Now we have observed that the E.M.F. at any point is proportional to

the sine of the angle through which the coil has then turned from zero; and it is convenient to take a number of points along this line, and at each of them erect a perpendicular proportional in length to the sine of the angle which that particular point represents. During that half of the revolution in which the sines are reckoned as minus—that is to say, from 180° to 360°—the perpendiculars should be drawn below the line, indicating the reverse direction of the E.M.F. and current. For instance, at 90° the sine will have the greatest value, viz. unity, while at 45° the perpendicular will be only 0·707, of that at 90°, because the sine of 45° is 0·707; at 270° the sine is −1, and therefore the perpendicular equal in length to unity is drawn below the line.

By joining the extremities of these perpendiculars we obtain a curve known as a sine curve, which at a glance indicates the

FIG. 126.



manner in which the E.M.F. rises and falls during one complete revolution of a simple coil; and the whole of the curve from A to B shows the fluctuation of the E.M.F. during two revolutions.

If in fig. 125, E X is taken as unity, it may represent the height of C or E, the highest points on the sine curve, and then E G will be the length of the perpendicular representing the electro-motive force at 60°, for E G is the sine of the angle E X G, which is the angle (60°) through which the coil has turned from the vertical position. Similarly, A_1 C (fig. 124) will represent the E.M.F. developed when the coil has turned through 30°, for A_1C is the sine of that angle.

The curve (fig. 126) shows that the E.M.F. at 90° is equal to that at 270°, but that it is positive in the one case and negative in the other.

Referring again to figs. 124 and 125, we observe that the 'effective area' of the coil, with respect to the lines of force which it embraces in the position A_1 B_1, is proportional to A_1 L, and in the position E F to E K—that is, A_1 L and E K are proportional to the number of lines of force passing through the coil in the two positions. Now, $\frac{A_1 L}{A_1 B_1}$ is the cosine of the angle through which the coil has already rotated (for the angles A_1 X A and P A_1 X are equal), or again it is the sine of the angle which the coil makes with the direction of the lines of force; as is also $\frac{E K}{E F}$. Taking, for simplicity, the equal lengths A_1 B_1 and E F as unity, we see that the number of lines of force passing through the coil in any position in a uniform field is proportional to the cosine of the angle through which it has been turned from its position at right angles to those lines, and also to the sine of the angle which it makes with the lines of force.

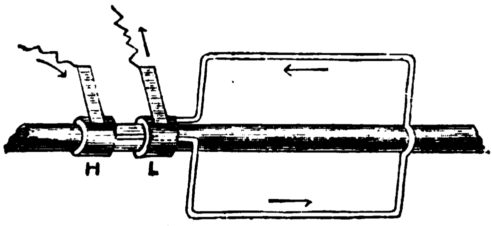
Currents which rise and fall in strength and change in direction in the manner indicated by the curve in fig. 126 are known as alternating currents, and a complete cycle as represented by the curve A C D E F is referred to as an alternation. For example, when the rate of alternation of a current is said to be 100 per second, it must be understood that the current rises from zero to a positive maximum, falls to zero again, and reaches a negative maximum, and again returns to zero, 100 times per second.

If, however, a rectangle or coil closed upon itself similarly to that shown in fig. 123 were employed, no useful work could be done, as the currents generated would simply circulate round the rectangle and be wasted in heating it. In practice we require to add to the rectangle some device which will enable us to lead the currents away to an external circuit and there make use of them. The rectangle might, for this purpose, be mounted on a wooden spindle (fig. 127), and its ends connected to two flat metal rings, H L, fixed a little distance apart on the spindle, contact being then made by means of a flat spring, or a wire brush, pressing against each of the rings. On rotating the spindle or shaft, the rectangle and rings would turn with it, and with a moderate amount of pressure the brushes would make good electrical contact with the

rings, the surfaces being kept clean by the rubbing. The contact brushes being fixed, it is easy to attach wires to them, and thus conduct the currents away to any desired point.

It remains now to show to what extent in practice we can comply with the conditions which theory teaches us should be followed if we wish to obtain a high electro-motive force. In the first place, we must make the value of N high—that is to say, the number of lines of force embraced and cut by the coil should be as great as the circumstances will permit. For a very small machine, permanent magnets may be used to supply the field, and for this purpose a horse-shoe magnet is found to be very convenient, but it should be bored out, or fitted with soft iron cheeks, of such a shape that there is just sufficient room for the wire coil to rotate between them. The steel should be strongly

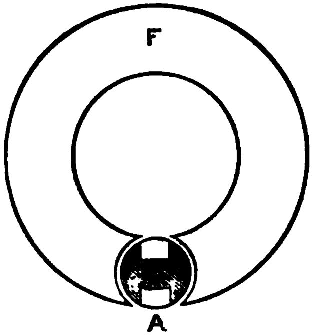
FIG. 127.



magnetised, and, if of considerable size, it should be laminated, or built up, of a number of thin magnets with their like poles adjacent. A circular magnet (fig. 128), divided at one part of the circle, and with just sufficient space bored out for the coil to rotate, is somewhat better than one of the ordinary horse-shoe pattern, although not so easy to make. Having obtained the magnetic field, the next thing is to get as many as possible of the lines of force to pass through the coil of wire. Iron here comes to our assistance once more, for, by winding the rectangle round a core of pure soft iron, we concentrate those lines which would otherwise stray, and the number passing through and embraced by the rectangle is greatly increased. It is almost superfluous to add that the actual area of the rectangle should be as great as practicable, provided that it is kept within the limits of the field, and since, as

we have seen, the induced E.M.F. is proportional to the number of active conductors joined in series, the wire may with advantage be wound into a coil consisting of a number of turns instead of only one. Any coil of wire in which currents are induced by its movement within a magnetic field is generally called an 'armature,' and the iron round which the wire is coiled is known as the 'armature core.' The core of one of the earliest forms of armature is shown in section at A, between the poles of the circular magnet F, in fig. 128, and although, when criticised in the light of our present knowledge, the design proves to be very faulty, it will serve very well to illustrate the principle. The armature in this case consists of a considerable length of silk- or cotton-covered copper wire, wound in the grooves of the shuttle-shaped piece of soft iron, A, which is usually about twice as long as its greatest width. It is provided at one end with a driving-pulley, and at the other end with a device, similar to that shown in fig. 127, for communicating the current to the external circuit. It will be seen that whenever the armature comes into the position shown in the figure the magnetic circuit is a fairly good one, the air-gaps between the pole-faces of the permanent magnet and the surface of the core not being very great, and the coil wound in the grooves of the shuttle will embrace a considerable proportion of the lines of force produced by the magnet. Good effects can therefore be obtained by rotating such an armature if the magnet employed is a powerful one. The speed of rotation must be high, but this can readily be obtained by any mechanical multiplying device, such as a pulley of large diameter driving a smaller one on the armature spindle.

FIG. 128.



Although the E.M.F. increases with the number of turns of wire on the armature, it is found that this increase is not by any means proportional, especially when the speed of rotation becomes very high. One important reason is because the conditions are very favourable for the 'self-induction' of the armature to make

itself evident. We have already seen that this effect becomes very marked with rapidly varying or alternating currents, and since, also, it increases with the square of the number of turns of wire, it is obvious that the number cannot be indefinitely increased with any prospect of satisfactory results. The increase of resistance, though not in itself such an important matter, also limits the length of the wire. It is, therefore, preferable to endeavour to increase the strength of the field and the length of the active limbs of the coil rather than the number of turns.

That the design of the shuttle armature is faulty may easily be proved, for, after being rotated for a little time, the iron shuttle or core gets quite warm, even though the armature coil may be disconnected or removed entirely. Now, this heat, so developed, represents a definite fraction of the energy expended in rotating the armature, which, as it does not reappear as electricity available for use, is to all intents and purposes wasted. It is an interesting fact that whenever a mass of metal is rapidly rotated in a magnetic field its temperature rises, the heat being the direct result of currents of electricity which are induced in the metal, and which are known as 'eddy' or Foucault currents. Their initial direction is at right angles to the lines of force of the magnetic field, and also at right angles to the direction in which the mass moves; therefore, in the shuttle armature, they travel lengthways along the iron core, completing their circuit in a more or less circular path in the iron (whence they gain the name of 'eddy' currents), and they follow the general law in reacting upon the field in which they are produced, in such a manner as to tend to stop the motion of the moving body. The E.M.F. of these currents is not high, but as the mass of the metal is great, and its resistance therefore small, the currents are sufficiently strong to considerably raise the temperature of the metal. In fact, it is possible to melt a piece of a metal which fuses at a low temperature, by simply spinning it rapidly in a very strong field.

It is evident that such a certain sign as this, that energy is being wasted, must not be ignored, and, since we cannot stop the tendency for the currents to be produced, the only alternative is to put difficulties in the way of their production.

In the case in question, the best method is to 'laminate' the

armature, or to build it up with a number of small discs cut to the required shape and bolted together, instead of using a solid piece of iron. The iron must be continuous in the direction in which the lines of force developed by the field-magnets have to pass through it, otherwise the efficacy of its action in concentrating these lines would be seriously impaired; while it must be discontinuous in the direction in which the eddy currents tend to flow, viz. at right angles to the lines of force. To meet these requirements the discs threaded on the spindle must be well insulated one from another, although, on account of the low E.M.F., a sheet of thin paper or a layer of varnish is, as a rule, sufficient. It is hardly necessary to adopt this precaution in the kind of machine we have been considering, which is very small, and only made to be driven by hand-power, but it becomes absolutely necessary, as well as economical, in the larger machines driven by steam-power.

At first sight it would appear, remembering that the E.M.F. developed in the armature coil varies as the rate at which the lines of force are cut, that the E.M.F. of a magneto-electric machine should be simply proportional to the speed of rotation, the strength of the field being invariable. But there are several causes which tend to prevent the increase of the E.M.F. developed by the augmentation of speed attaining this proportion, the principal being the eddy currents produced in the core, the electro-magnetic reaction of the current in the armature upon the field produced by the field-magnets, and the self-induction of the armature. It is important to notice that when a current is flowing round the armature coil the whole armature is in reality an electro-magnet, and it acts as such upon the poles of the permanent horse-shoe magnet which supplies the field, this reaction, as in every similar case, tending to stop the motion of the armature. If, however, the armature is forcibly rotated against this tendency, the result is that the magnetic field is distorted and dragged somewhat out of its true position, and, as the current in the armature rapidly alternates from zero to a maximum, this dragging effect will also vary considerably, with the result that the field will be kept in a state of oscillation and its uniformity destroyed. The maximum current in the armature becomes higher as the speed is increased, if the external resistance is constant, and the distortion of the field

is then greater, the result being a tendency to prevent the E.M.F. rising in proportion to the speed. Furthermore, as the iron core has a greater number of lines of force due to the current passing through it when the current increases, its permeability may also become appreciably lower, and fewer lines of force due to the permanent magnet may then pass through the core and be cut by the active conductors of the coil.

Besides the waste due to eddy currents, which increases very rapidly with the speed, the effect of the self-induction of the armature also becomes strongly marked, retarding the rise and fall of the current. In fact, were we able to plot a curve showing the rise and fall of a currrent in this shuttle armature, we should find it somewhat similar to that given in fig. 126, for the rise and fall of the electro-motive force, but with the important difference that it would be shifted more or less to the right, its maxima and minima being less in value and occurring later than would be the case if the armature had little or no self-induction. Owing to the fact that it is not possible to construct a practical armature with as little self-induction as the single rectangle, or to make its active limbs cut the lines of force of a uniform field in such a regular manner as is done by our experimental rectangle, we do not in practice obtain a perfect sine curve for the E.M.F. curve of any armature, but only an approximation thereto. The approximation is, however, a very close one in the case of some machines in which the field is very powerful, and in which no iron core is used in the armature.

We shall presently be better able to consider the reaction on the field in connection with a different type of armature, but we may here remark that it is one of the most important points to be borne in mind in deciding how a more powerful and efficient machine can be obtained.

Now, if we wish to obtain in any given case an increase in the value of the electro-motive force obtained, there are four methods available.

1. By increasing the speed of rotation.

2. By increasing the number of turns of wire in the armature, thus increasing the number of active limbs joined in series, which cut the lines of force. This method, as already pointed out, adds

not only to the resistance, but also to the self-induction of the armature.

3. By increasing the area of the armature coils, or by making the core more massive, for in either case the number of lines of force cut by the coil is, within certain limits, increased.

4. By increasing the strength of the field.

The last-named method is the freest from objections, and it has the all-important advantage that, the stronger the fixed field is, as compared with that developed by the armature, the less is the reaction and consequent distortion of the field.

The necessity for a strong field is so apparent that powerful electro-magnets are now usually employed, but, as might be expected, in all the early efforts to construct a dynamo-electric machine, the field was obtained by means of permanent magnets. But the method of cutting the 'armature' wires by lines of force was not by any means restricted to the rotation of the armature in the field. One very interesting method was applied by Wheatstone, and is still largely employed to generate short intermittent and comparatively feeble currents. The wire in which the currents are generated is wound on, let us say, two bobbins which are fitted with soft iron cores, and fixed one on each pole of a powerful permanent steel horse-shoe magnet. Many of the lines of force due to this steel magnet pass through the soft iron cores, and, in the absence of a keeper or armature, complete the magnetic circuit across the air-space at the top in the well-known curved form, but no current is generated in the wire while they are undisturbed. When, however, a soft iron armature is placed across the ends of the cores and very near to them, a great many of the lines of force rearrange themselves and pass through this soft iron armature. These lines, in moving to their new positions, cut the convolutions of the coils and generate therein an electro-motive force which, if the circuit is completed, gives rise to a momentary current. When the armature is entirely removed the original arrangement is re-established, and the cutting which then takes place also generates a momentary current, but in the opposite direction to the previous one. The most convenient way of rapidly shifting the soft iron armature is to mount it on a spindle and rotate it before the ends of the cores which project through the coils.

Hitherto no large machines built upon the foregoing principle have been practically used, and this is, perhaps, surprising, as the advantages due to the simplicity of construction are many and important. The only moving part of the apparatus is a mass of iron which, if truly balanced, can be rotated at a very high speed without involving any mechanical difficulties, and as the coils are fixed, connection between them and any external circuit can easily be made. Mr. W. M. Mordey has, however, described several methods of applying this principle to large machines, and he has constructed a model of one form which certainly appears to be of a simple and practical character.

The armature and field coils are each wound in the form of a ring of rectangular section, the former being of larger diameter than the latter, and they are placed concentrically, with the field coil inside the armature coil. A number of pieces of iron are placed in such a manner that the rotation of an iron keeper causes many of the lines of force at one moment to embrace both armature and field coils, and at the next moment to pass round the field coil only; and as these lines, during their movement from one position to the other, cut the armature coil transversely, alternating currents are induced in that coil.

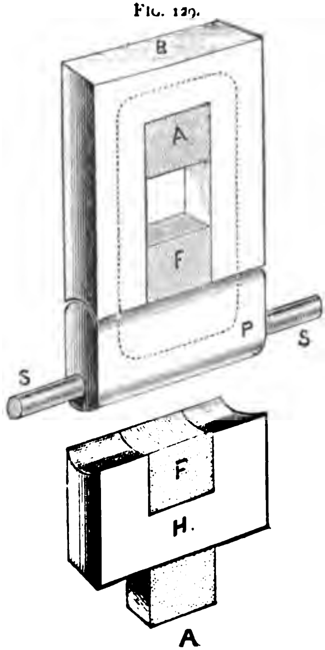
The principle may be more easily grasped by a consideration of the arrangement illustrated in fig. 129, in which F F show the field coil in section at two points at opposite extremities of a diameter, and A A show sections through two similar points of the armature coil. B is a mass of iron which embraces both the armature and field coils on three sides, while H is a piece, equal in cross-section but having shorter limbs, which embraces the field coil only on three sides, the armature coil being placed outside the yoke. P is a keeper carried by the shaft, S, which can be rotated rapidly, the shaft being at the centre of the two circular coils, F F and A A.

If a powerful current is sent through the field coil F F, a large number of lines of force will be developed, and their arrangement will largely depend upon the iron pieces, H and B, but more especially upon the position of the keeper P with respect to H and B.

When P is situated as shown in the figure it forms with B an

almost complete magnetic circuit of low magnetic resistance round both coils A and F, and nearly the whole of the lines generated by the field coil in the vicinity of this iron circuit will also embrace the armature coil. In springing into this position (shown by the dotted line), the lines cut the armature coil transversely from the inner side, and give rise to a current, depending in E.M.F. upon the number of lines and the rapidity with which their position is changed. When the keeper is moved away there is a considerable air gap, offering a high magnetic resistance at the ends of the limbs of B, and consequently many of the lines of force collapse upon the coil F, cutting the armature from the outside as they pass into their new positions and generating an E.M.F. in the opposite direction to the previous one. Not only is the magnetic resistance of the path round the two coils made greater by the removal of P from the position indicated in the figure, but as P rotates it reaches a position where it acts as a keeper to the iron piece H, which embraces the field coil only, so that an almost complete magnetic circuit is then formed round the field coil, and nearly the whole of the lines of force pass through H and P and very few extend round A. Therefore, if the keeper P is rapidly rotated, the armature coil will be cut by a number of lines of force as they take up new positions, first outside and then inside it. It is evident, however, that, with such a simple arrangement as that shown in fig. 129, it would not be possible to make all the lines of force developed by the field coil take either the one path or the other, many of those surrounding the coil at a distance from the fixed iron pieces being but little affected by the movement of the keeper,

FIG. 129.

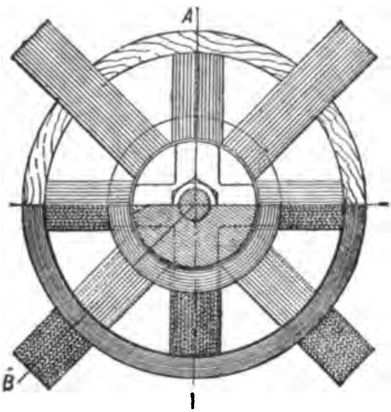


but in designing an actual machine care would be taken to so dispose the iron that most of the lines of force would be influenced.

In Mr. Mordey's machine there are four iron pieces similar to B, embracing both armature and field coils, placed 90° from each other as shown in fig. 130. Between these are placed four shorter pieces similar to H, outside the field but inside the armature wire.

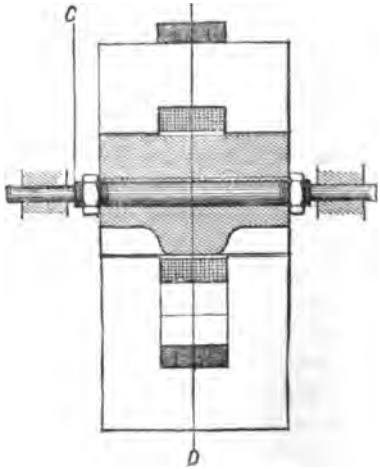
The lower half of fig. 130 is shown in section; fig. 131 is also in section, the upper half from A to the centre of the shaft, and

FIG. 130.



Section through C D

FIG. 131.

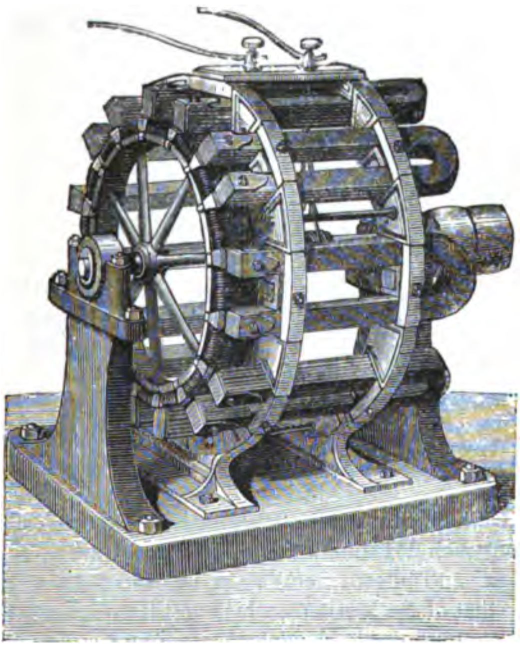


Section through A B

the lower half from the centre of the shaft to B, so as to obtain a section through both a short and a long iron limb. The mass of cast-iron which plays the part of a keeper may be described as a cylinder having four deep sector-shaped notches cut at each end. If viewed end-on, a section near one extremity would be in the form of a cross, while a section through the middle would be circular. In the figures each arm of the cross is shown as forming a keeper to one of the smaller iron pieces embracing the inner or field coil only, and consequently few of the lines developed by the field coil extend round the armature coil. In the lower part of

fig. 131 the deep notches are opposite the iron pieces which embrace both coils, forming a great break in the magnetic circuit, and this is also shown in fig. 130. On rotating through an angle of 45°, however, the keeper completes the various magnetic circuits in such a manner that most of the lines of force extend round both coils. These two alternate conditions succeed one another rapidly as the keeper continuously revolves. As the lines

FIG. 132.

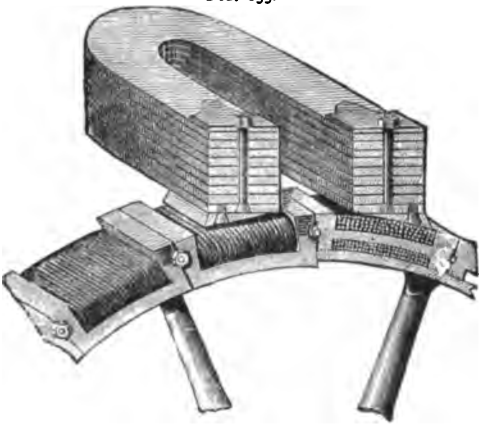


of force are rapidly carried backward and forward past the armature coil, they generate therein the desired currents, but they also give rise to eddy currents in the masses of iron through which they are projected. The direction in which these eddy currents would be set up is parallel to the currents in the armature core, and therefore the masses of iron should be laminated so as to give discontinuity in this direction, while continuity is retained in the

path of the lines of force. Consequently the iron should be built up of a number of thin U-shaped sheets, insulated and bolted together. One advantage pertaining to such a machine is that, since neither the armature nor the field coils rotate, there is no special device needed, and no difficulty whatever in collecting the currents from the armature or in passing a current of the desired strength through the field coil.

Machines in which steel magnets are employed for producing the field are often called magneto-electric machines or generators, and are sometimes regarded as a class altogether distinct from

FIG. 133.



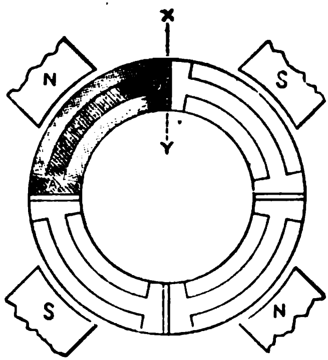
machines in which the field is developed by one or more electro-magnets, but such a distinction is altogether arbitrary.

The best and most useful form of the so-called magneto-machines is that of De Meritens, which is still extensively employed for lighthouse purposes. A general view of a simple form of this machine is shown in fig. 132.

The armature consists of a series of sixteen coils fixed round the periphery of a wheel of brass or other non-magnetic material. The method of constructing and fixing the coils is shown in fig. 133, one coil and a portion of the rim of the wheel being in section. A flat core of soft iron, C (composed in the more recently built machines of eighty pieces of soft sheet iron one millimetre

thick and stamped out to shape) is provided with rather large pole-pieces, and has wound over it about 1½ pound of copper wire. Each coil is distinct from the others, the cores of two adjacent coils being magnetically insulated (as at X Y, fig. 134) by a thin strip of copper. The wheel or frame to which the coils are attached is furnished with a number of substantial lugs. The ends of the pole-pieces of the cores are placed between these lugs, and, being provided with semi-cylindrical grooves of the necessary dimensions, the whole are firmly fastened together by bolts. It is important to notice that the extensions of the cores reduce the air-space between the poles of the permanent magnets and the cores to a minimum, and therefore conduce to the projection of the highest possible number of lines of force through the coils, and consequently to the generation of the maximum attainable E.M.F.

FIG. 134.

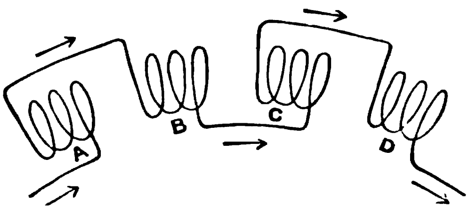


The field is produced by a series of eight compound steel magnets fixed horizontally round the armature ring, by means of a brass framework. The inner surfaces of the magnets are provided with small soft iron pole-pieces, which further reduce the air gaps between the magnets and the armature cores. The magnets are disposed uniformly round the ring, the coils passing, therefore, north and south poles alternately.

The distance between the limbs of each magnet being exactly equal to that between the opposite poles of the adjacent magnets and this distance being also equal to the length of each coil, it follows that, on the armature being rotated, each coil passes sixteen alternate poles in one revolution. The manner in which the currents are induced can best be appreciated by a reference to fig. 134, where the ring has only four coils which rotate between a similar number of magnet poles, N S N S, one coil or segment, A B, being shown in section. When the coils are in the position shown,

the minimum number of lines of force is, at that moment, passing through them and the E.M.F. reaches its highest value, but after traversing another 45°, the core-extensions will be opposite the field-magnet poles, and the coils will then embrace the maximum number of lines of force; at this latter point the reversal of the current takes place. The coils being all wound in the same direction and all connected together in series, it is evident that the current in the adjacent coils on either side will be opposite in direction to that taken by the current in A B, as they are passing through fields developed by the south poles. Were the adjacent ends of the neighbouring coils connected together, the electro-motive forces in the various coils would therefore neutralise each other, and no current could be urged through the external circuit. This difficulty, however, can be readily obviated, as will be made

FIG. 135.



evident by a reference to fig. 135. Instead of connecting the adjacent ends of two coils together, the connection is made between their two similar ends—that is to say, the end of the coil A to the left hand is connected to the similar end of B, while the end of B to the right hand is connected to the right-hand end of C, and so on. In this way, although at any moment the currents in the various coils are generated in opposite directions, they, instead of neutralising one another, are made to take one common direction through the circuit. This does not, of course, alter the fact that the current delivered by the dynamo is an alternating one; that is to say, as the coils advance from one set of magnet poles to the next, the direction of the current in the whole of the coils is reversed, and therefore, also, the direction of the current in the external circuit. The whole of the coils in fig. 132 being joined together in series, the total E.M.F. developed is sixteen

times that developed in one of the coils, and further, the current will alternate in direction at a rate greater by eight times than would be the case if only one magnet were employed and the armature were rotated at the same speed. In the more recent form of this machine there are five armature rings, each with its sixteen coils and eight compound magnets. The latter are, for very apparent mechanical reasons, fixed radially instead of longitudinally, and they have a total weight of about one ton. The eighty coils are divided into two circuits which are brought to four collecting rings mounted in pairs on an insulating bush fixed on the principal shaft of the machine and, therefore, revolving with it. This type is almost exclusively employed for lighthouse purposes, and within fairly wide limits its E.M.F. varies almost directly with the speed of rotation. It is unusually strong in design, the parts being also fixed together in such a manner as to permit of their being, when defective or injured, very easily removed for renewal or repair.

It has been pointed out that the best means available for increasing the E.M.F. and therefore, also, the strength of the current yielded by a machine, is to increase the strength of the field. Now there is a limit, which is soon reached, to the field attainable with permanent steel magnets even if built up of thin sections, because the maximum number of lines of force which can be urged through steel is comparatively low, and even then only a portion of this number can be permanently retained ; whereas with good soft iron a far greater number can be forced through, and if the lines of force are produced by a current circulating in a coil of wire enveloping the iron, the question of retentivity does not arise. Consequently, to develop a given amount of power, a machine in which the field is produced by electro-magnets is considerably smaller than one in which steel magnets are employed.

Primary batteries might be, and in fact were at one time, used to furnish the current for the purpose of exciting the field-magnets, but it is far more economical and advantageous to obtain this current by means of a small dynamo. This auxiliary machine, which we will for the present refer to as the exciter, must be able to excite itself—that is to say, it must be able to supply the requisite current for its own field-magnet coils and to yield a current con-

tinuous in direction. Descriptions of many such dynamos will be found in the following chapters.

We can scarcely do better, in commencing a study of the modern forms of alternating machines, than describe one which would appear to follow as a natural evolution of the De Meritens. Such a machine, excellent alike in its mechanical and its electrical details, is the one designed by Mr. Gisbert Kapp, and illustrated in fig. 136, which also shows on the right-hand side the small exciter mounted on an extension of the main bed-plate, its armature being also fixed on to the main shaft. The field of the alternator is produced by two crowns of short cylindrical electro-magnets, the cores of which are of wrought iron. These cores are fixed at one end into cast-iron yoke-rings, and provided at their inner ends with rectangular pole-faces, between which the armature revolves. In the particular machine illustrated there are twenty-eight of these magnets, fourteen in each crown, the diameter of each core being $4\frac{1}{8}$ inches. Each magnet core is wound with 186 turns of thick insulated copper wire, the whole of the coils being ultimately joined in series and offering a total resistance of 1·76 ohm. The winding of these coils is such that the magnets forming each of the crowns alternate in polarity, while the opposing faces are of the same polarity. One continuous core is used for the whole of the coils in the armature, and is built up by winding thin band-iron upon a cast-iron supporting ring, the layers being insulated by varnish, to prevent as far as possible the flow of eddy currents. The section of this core is almost rectangular, with its greater dimension radial. The armature wire offers a resistance of 1·8 ohm, and is divided into fourteen coils, wound over the core ring, each coil consisting of eighty turns of insulated wire 120 mils (0·12 inch) in diameter, wound in two layers.

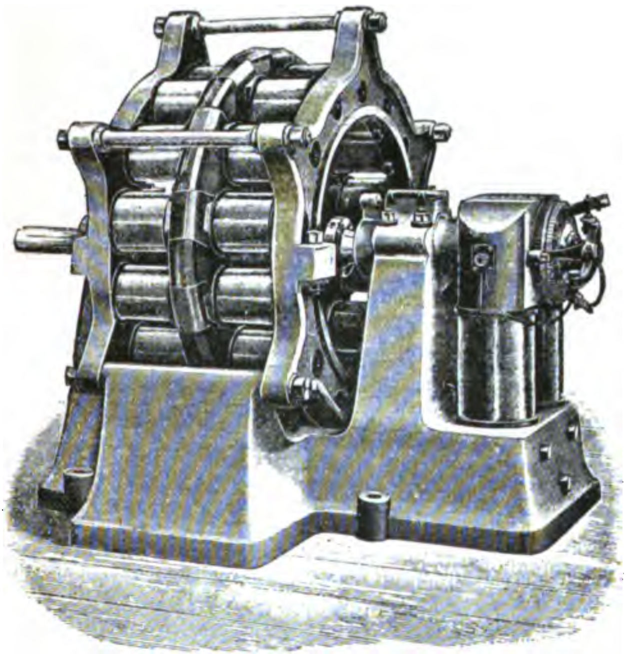
The manner in which the currents are generated as the armature rapidly revolves through the alternate fields is very similar to the method of production in the De Meritens machine. In this case, however, the lines of force enter and leave the armature at both sides of the flat ring which constitutes the armature core, instead of at one side only.

The extremities of the armature wire are connected to a pair of brass rings on the shaft, from which the current is collected by

copper brushes. As the E.M.F. of these machines is usually high, it is a frequent practice to place the collector-rings on opposite sides of the armature, so that the attendant cannot touch both brushes at the same time.

The cast-iron bed-plate is very substantial, and the method of bolting the yoke-rings to it and to each other is clearly shown in the illustration.

FIG. 136.



When this machine was driven at 600 revolutions per minute, the exciting current being 9 amperes, the total E.M.F. developed on open circuit—that is to say, with the collecting brushes disconnected from the external circuit—was 1,000 volts. When the field was strengthened by increasing the exciting current to 21 amperes the E.M.F. rose to 2,400 volts. With the same exciting current and the armature of the alternator joined through an external

resistance and a dynamometer, a current of 30 amperes was generated, the potential difference at the terminals then being 2,000 volts. The available output was therefore 60,000 watts. The power absorbed in exciting the field-magnets was 775 watts, or about 1·3 per cent. of the total output, the loss in the armature due to its resistance being 2·7 per cent.

When all the coils are joined in series, the total E.M.F. at the collecting brushes is equal to that developed by one coil multiplied by the number of coils, but occasionally, in such machines, a lower E.M.F. with a heavier current is desired, and then the coils are joined in parallel, either in two sets, or as may be required. An equal E.M.F. might, of course, be obtained with fewer coils and pole-pieces, provided the number of lines cut in the same time and the number of convolutions in series are made the same; but the great advantage accruing to the use of a large number of pole-pieces and coils is that a rapidly alternating current can be obtained without rotating the armature at an enormous speed, and so introducing mechanical difficulties.

It has already been pointed out that the current, or rather currents, resulting from one complete rotation of a coil in a simple field, which may be represented by the curve A C E F in fig. 126, is called an 'alternation,' and any similar pair of currents developed by any armature with any field is also called an alternation. In estimating the rapidity with which a current is reversed, it is better to speak of the number of such alternations which take place in a second, rather than the number of reversals. The majority of the machines at present in use work at from 80 to 100 alternations per second, and to obtain the latter number a single coil in a single field would have to be driven at 6,000 revolutions a minute. But although a rapidly alternating current can be easily obtained with a large number of pole-pieces, a disadvantage results from the fact that these pole-pieces alternate in polarity all round each crown. Each pole-piece is flanked on either side by others of opposite polarity, and a large percentage of the lines of force leak across between adjacent limbs, instead of passing through the armature core, and are wasted, since they cannot be cut by the conductor. This disadvantage also exists in the two machines next to be described, where the leakage is somewhat increased on

account of the fact that the armature is not provided with an iron core. In fact, it is not an unusual circumstance for nearly half

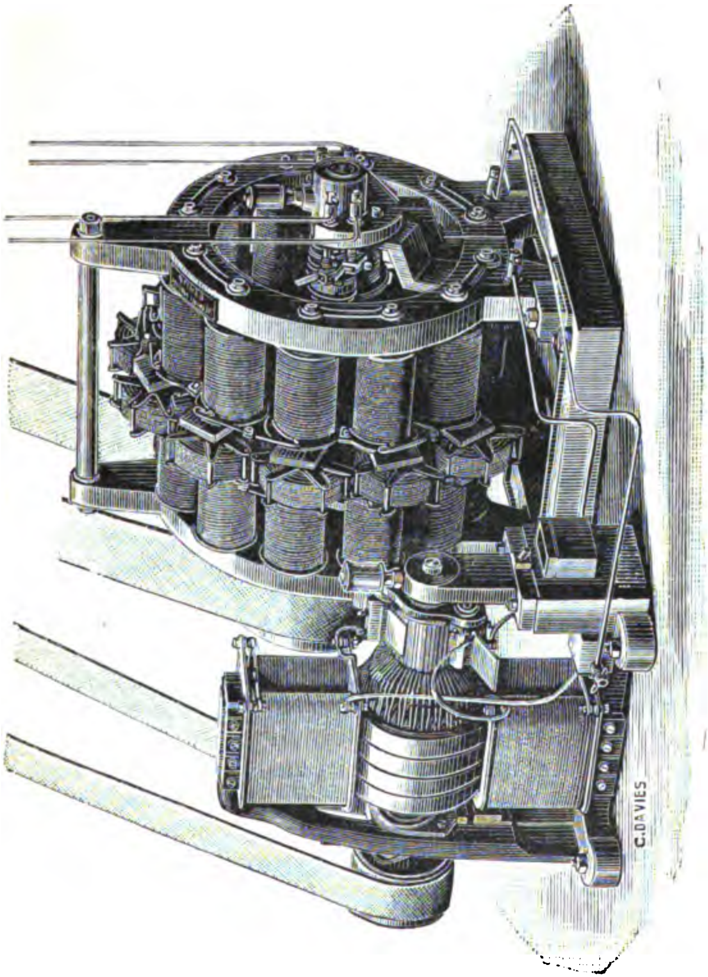


FIG. 137.

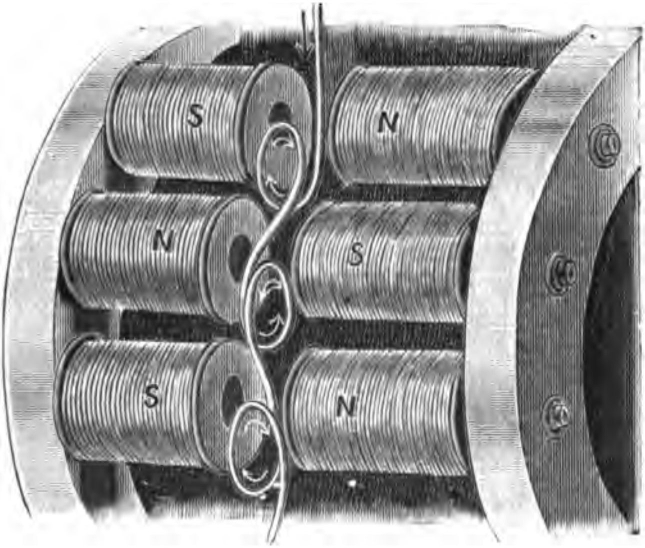
the lines of force developed by the field-magnets to be rendered inoperative by leakage in such machines with coreless armatures,

but the absence of iron in which repeated changes in the direction or the number of the lines of force is taking place obviates the loss by eddy currents and hysteresis, and more than compensates for the loss by leakage.

The form of alternating current dynamo constructed by Messrs. Siemens is illustrated, together with its exciter, which is driven independently from the main shaft, in fig. 137. The field-magnets present an appearance similar to that of those in the Kapp machine, consisting, as they do, of two opposing crowns of cylindrical electro-magnets, but with the essential difference in the winding that the facing pole-pieces are of opposite polarity. The adjacent pole-pieces on each frame resemble the Kapp in being also of opposite polarity. The arrangement is clearly indicated in fig. 138, which shows three pairs of magnets and three ideal armature coils, and it will be evident that, with this disposition, the lines of force pass from pole to pole, straight across the armature space. The plane of the armature coils is coincident with the plane of rotation, so that the coils, in rotating, cut through a series of powerful fields with the lines of force alternating in direction. As the direction of the lines of force through any adjacent pair of coils is opposite, it is necessary, in order to prevent the electromotive force induced in one coil neutralising that induced in the other, either to make the connections as in the case of the De Meritens (fig. 135), or to wind the bobbins as right and left-handed helices alternately, after the manner shown in fig. 138. The number of armature coils being the same as the number of fields, it follows that all these coils are, at any particular moment, equally active. Referring to fig. 138, in which the direction of rotation is left-handed, it will be seen that the coils are just leaving the pole-pieces, and currents are being generated in the directions indicated by the small arrows. The E.M.F. increases until the coils arrive at positions midway between the pole-pieces, where it is a maximum, because at that moment the forward half of each coil is cutting lines of force which pass in one direction, and the rear half other lines due to the next pair of opposing magnets, which pass in the other direction; and the induced currents, flowing outwards in one half, and inwards in the other, coincide in direction round the coil. Every line of force, then, cut by the coil is

being usefully employed. When this middle position is passed, the number of lines cut by the front half increases, while the number cut by the rear half decreases, and this continues until both halves of the coil are cutting lines of force all due to one pair of opposing magnets, and which are therefore all in one direction. Consequently, an opposing E.M.F. is induced in the rear half, the value of which increases until the coil is exactly opposite the pole-pieces, when both halves will be cutting an equal number of lines

FIG. 138.



of force, which are all in the same direction; whence equal and opposite E.M.F.'s will be induced in the two halves of the coil, and will effectually neutralise each other. At this point, then, when the coils embrace the maximum number of lines of force, the reversal in the direction of the current takes place, for on passing forward, the front half of each coil is cutting less, instead of more, lines of force than the rear half. The number of alternations in each revolution corresponds, therefore, with the number of coils, or, what is the same thing, with the number of fields.

In practice, the machine is built up on a cast-iron bed-plate, to which are securely fixed two circular frames, united and held in position by a stout iron stay. An equal and even number of electro-magnets is fixed to each frame, the cores being turned down so as to fit into holes drilled through the frames. These ends are likewise tapped, and, nuts being screwed on on the outside, the electro-magnets are fixed firmly in position. The inner ends of the cores are furnished with radial pole-pieces, which by reducing the air space between the opposing pole-faces concentrate the fields and increase the number of lines of force passing through the rotating armature coils. The armature coils, instead of being circular, like those in fig. 138, are pear-shaped, and the armature is fitted up by attaching the coils, which are wound over wooden cores, round the circumference of a disc or wheel which is mounted on the shaft.

A general view of the machine designed by Mr. Ferranti is given in fig. 139, the particular one illustrated being constructed to develop 150 electrical horse-power. The field-magnets are similar in principle to those in the Siemens Alternator, and consist of two sets of electro-magnets, attached to massive iron rings forming the yokes, the magnetisation of the pole-pieces round each ring being alternately north and south, and the facing pole-pieces also of opposite polarity, so as to develop a series of very powerful fields, alternating in direction across the space through which the armature coils sweep. The framework carrying each crown, or ring, of field-magnets is divided vertically into two halves, which, on being unbolted, can be slid out of position in a direction at right angles to the shaft, and so afford access to the interior for cleaning or repair.

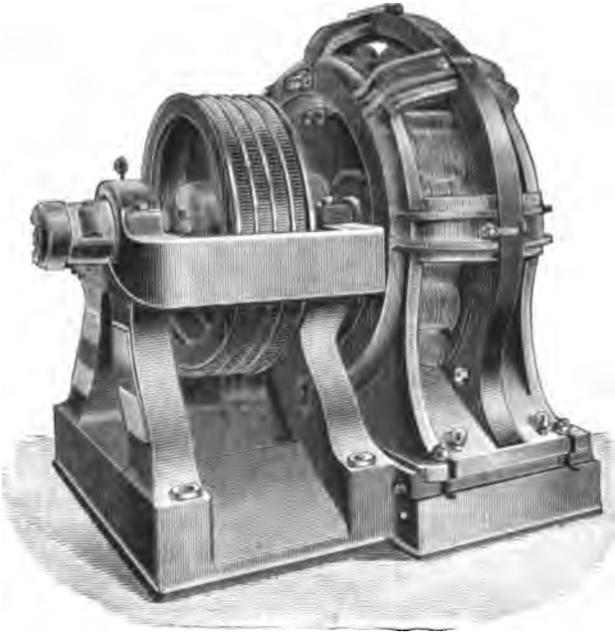
The machine is driven by rope gearing, the pulley, as shown to the left in the figure, being grooved for the purpose.

The method of securing the cores of the magnets to the yoke-rings is unique. The wrought-iron cores of half the magnets forming each crown are fixed in a mould, and the half of the yoke-ring is then cast on to them, making in that way the surest and simplest form of magnetic connection between the wrought- and cast-iron sections of the field-magnets.

The distinctive feature of the original Ferranti machine con-

sisted in the construction of the armature, which being interesting from a theoretical point of view, is illustrated in fig. 140. The heavy zigzag line represents half of the armature, which consists of a copper ribbon bent round and bolted to a non-magnetic framework attached to the shaft. The faces of one set of field-magnets are shown behind the armature strip, and it will be seen that the space occupied by each complete bend in the armature is

FIG. 139.

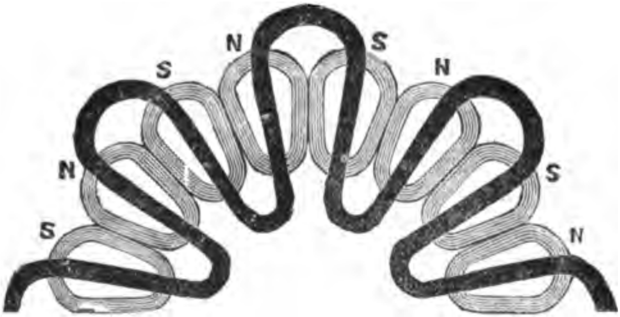


equal to that of two field-magnet coils, the distance between two straight radial portions being equal to the width of one coil. When the armature is rotated all the radial portions of the strip are usefully employed in developing E.M.F. At any particular moment each of these portions is cutting lines of force in a direction reverse to that of its immediate neighbours. Consequently, opposite currents are at any moment generated in

adjacent radial portions, one set flowing radially inwards, and the other set radially outwards, but the zigzag winding naturally makes all the simultaneously generated currents travel round the armature in one common direction.

Alternate current machines being usually required to develop a high electro-motive force, such a simple winding is of little service, although it answers the purpose admirably when only a low electro-motive force is required. The E.M.F. developed is, of course, proportional to the actual number of the straight radial portions of the armature wire which cut the lines of force transversely. It is manifest that to greatly increase this number in a simple zigzag form would be impracticable, from the fact that the

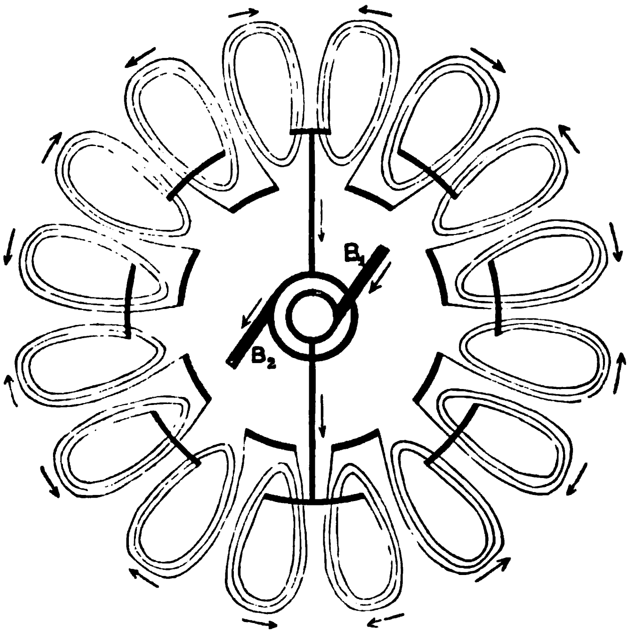
FIG. 140.



number of field-magnet bobbins must always be twice that of the loops in the armature. The practice, therefore, is to obtain the desired increase in the number of active conductors by coiling the copper ribbon several times round a number of non-magnetic, pear-shaped bobbins. Then, if the whole of the bobbins are connected in series, the total E.M.F. developed will be equal to the E.M.F. of one multiplied by the total number of bobbins. But it is no unusual thing for a machine to develop an E.M.F. of several thousand volts, and, were this method of joining-up adopted, serious difficulties in maintaining insulation would arise at the two ends of the series where connection is made with the external circuit, owing to the fact that there the potential difference between the two adjacent coils would be the maximum developed by the

machine. Consequently, the armature coils are always grouped in parallel sets, generally two, as shown in fig. 141. By the arrangement here illustrated, the potential difference between any two adjacent wires can never be more than that developed in one bobbin, but the total E.M.F. of the machine is reduced to half of what it would be were the whole of the coils joined in series. Fig. 141 shows very clearly the way in which the coils are joined

FIG. 141.



together. Since the current is induced in the opposite direction in adjacent coils, it becomes necessary to connect alternately the two inner and the two outer ends of the coils together, otherwise the E.M.F. of one coil would neutralise that of its neighbour. The currents generated alternate rapidly, but the arrow-heads indicate the direction which the current takes at one particular moment in the various parts of the armature. B_1 B_2 are the brushes connected

to the external circuit, by means of which the currents are conveyed from the insulated metallic rings on the armature shaft.

A few details concerning a Ferranti dynamo designed for an output of 625 horse-power will be instructive. The mean diameter of the armature is 7 feet, and it comprises 40 coils, joined up in two sets of 20. The copper ribbon is 12·5 millimetres wide, and 0·75 millimetre in thickness, twenty-five turns being wound over a core of brass (laminated at right angles to the direction of rotation and insulated with asbestos) to form each coil, the convolutions being insulated by means of a continuous strip of fibre, 0·5 millimetre thick, wound on with the copper. The inner end of each coil is connected to the brass core, these cores being also electrically connected together in pairs, as indicated in fig. 141. In a somewhat similar manner the outer ends of the coils are connected together in pairs through the supporting framework.

The peripheral velocity of the armature is 6,050 feet per minute, and, manifestly, special attention has to be paid to the method of fixing the coils to prevent their flying out. Each of the laminated brass cores already referred to is solid at the inner end—that is to say, the end nearest the driving shaft—and an insulated bolt passed through a hole drilled in this solid portion parallel to the shaft firmly secures the core and its coil to the revolving framework.

The external potential difference developed is 2,400 volts, but by the adoption of the device shown in fig. 141 the maximum potential difference between the wires on neighbouring coils is reduced to 120 volts. The resistance of the armature from brush to brush is 0·176 ohm.

The field-magnets are excited by a separate direct-current dynamo, twelve electrical horse-power being thus absorbed. There are 80 bobbins on each yoke-ring. The distance between the faces of opposite pole-pieces is only 0·875 inch, which is one of the important advantages pertaining to this form of armature, and enables iron cores for the armature coils to be dispensed with, as the nearness of the opposite pole-faces reduces the wasteful leakage between adjacent pole-pieces.

One of the most interesting and most important machines for

the generation of alternating currents is that designed by Mr. W. M. Mordey, and illustrated in fig. 142. There are in this

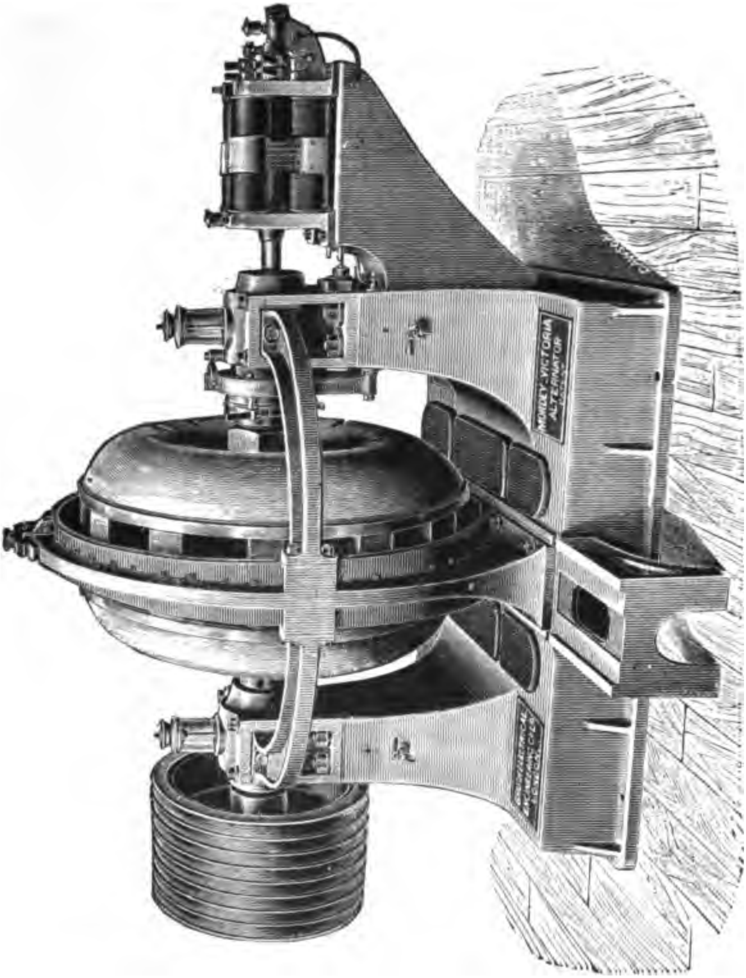


FIG. 142.

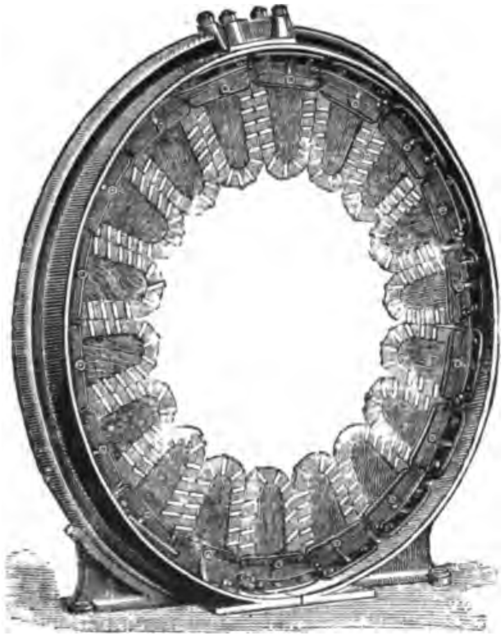
machine two departures from the practice adopted in constructing the machines previously described. In the first place, the arma-

ture is fixed, and the field-magnet rotated; and, in the second place, the lines of force in the various fields projected through the armature coils are all in one direction, the pole-pieces on one side of the armature being all of north polarity, and those on the other side of south polarity. There is consequently no tendency to leakage between the adjacent pole-pieces, but the space between the opposing pole-faces is kept as small as practicable, not only in order to reduce the magnetic resistance, but also to prevent the spreading of the field, because it is necessary that any one armature coil shall at one moment embrace as many as possible, and at the next moment as few as possible, of the lines of force.

The armature, which is shown in fig. 143, consists of a number of coils of copper ribbon, wound on flat pear-shaped cores either of paraffined wood or porcelain, the different layers or turns of ribbon being insulated one from another by an insulating strip of the same width, which is wound in with them. The whole of the turns in each coil are bound together with strips of prepared tape. The outer or broad end of each coil is clamped by two short bolts between German-silver plates bearing against ebonite insulating sheets, and through these plates and the core of the coil is placed a third bolt, which also passes through a slotted hole in the internal flange of the frame, and so secures the coil in position. Each coil is also provided with a radial adjusting screw, one end bearing against the head of the coil and the other end against the inner face of the external flange; and when the third bolt mentioned above is loosened, the coil can be adjusted accurately in position by being urged radially inwards or outwards. The ends of adjacent coils are electrically connected by stiff conductors brought out through porcelain insulators as shown in the figure. The metal supports, which do not anywhere come between the poles of the field-magnets, are almost entirely beyond the magnetic field, and in this way the generation of wasteful eddy currents is reduced to a minimum, any slight loss that might arise from this cause being still further reduced by the employment of German silver for the brackets and bolts, as the high resistance of this alloy prevents the generation of any but exceedingly feeble currents. The gun-metal supporting ring, which is bolted to the bed-plate of the machine, is in two portions, being divided in a

vertical diametrical line. These two parts, after having received the coils, are bolted together and to the bed-plate, the field-magnets being, however, previously placed in position. By this device single coils, should they become faulty, can be easily and quickly removed for renewal or repair; or each half of the armature can be removed without difficulty by sliding it on to the stool shown in the figure.

FIG. 143.



The shape of the field-magnet is remarkable, and differs altogether from that of any other machine previously constructed.

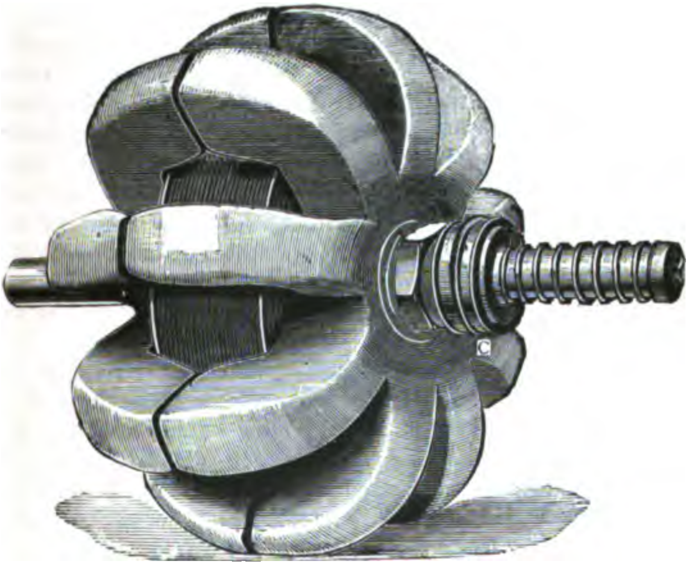
It consists of a single electro-magnet built up in the following manner: A short cylinder of iron, through the axis of which the shaft passes, forms the core of the magnet, and is wound with a single exciting coil. To each end of this cylinder or core is attached a massive iron casting of peculiar form, which will be best under-

stood from fig. 144. Each casting consists of a number of horns or claws, which bend over from their common junction, so that the extremities of the two sets of pole-pieces approach within a very short distance of each other, the narrow polar gap or slit thus formed being only just wide enough to contain the armature coils without touching them when the entire field-magnet is revolved. The ends of the 'exciting' coil (which is to be seen inside the pole-pieces in fig. 144) are connected to collector-rings on the shaft, as shown at C to the right of the figure. These might be dispensed with, and the exciting coil, as well as the armature, might be made stationary. The core and its pole-pieces would then be the only portions revolving, and the electrical effect would be the same, but serious mechanical difficulties would arise in fixing the coil. Hence, it is far preferable to attach it to the rotating cylinder. The simplicity of this form of field-magnet is one of its great features, as a single exciting coil suffices for a machine of any size, speed, or number of alternations. The heavy rotating field-magnet acts very efficiently as a fly-wheel, and ensures steadiness in running, effectually neutralising, within certain wide limits, any pulsations due to irregularity in the stroke of the engine, and it is also advantageous when two or more machines are run so as to feed the same circuit in parallel. The insulation of the armature coils, as well as their connection with the external circuit, is also simplified, and being stationary they need only to be supported with a view to resisting the drag of the field, which is parallel to the plane of the coils. The armature is stiffened and held in its vertical position by substantial horizontal brackets bolted on to the bearing-standards.

The method of joining the armature coils together is similar in principle to that illustrated in fig. 141, the inner ends of the coils being joined together by short copper rods on one face of the frame, and the outer ends on the other face. The position of one of these sets of connecting wires or rods can be seen in fig. 143, although it may be mentioned that in some machines the whole of the connections are placed on one face of the armature. The number of alternations during each revolution is the same as in the case of a Siemens or a Ferranti machine having an equal number of armature coils, but there are only half as many pole-

pieces as would be required for either of those machines. This arises from the fact that the current in each coil is reversed at that moment when it is between two opposite pole-faces, and again when it is midway between two adjacent pairs of pole-pieces—that is to say, at the moment when it has the maximum number of lines of force thrust through it, and again when it embraces the minimum number. It will be observed that in this machine the direction of the lines of force through the armature coils is

FIG. 141.



never reversed, the electro-motive force being produced by alternating the number of lines of force embraced by the coils between a maximum and a minimum.

Since the armature coils are similar as regards shape and the length of ribbon wound on them, and as the various fields projected through them are at any moment equal, the E.M.F. of any one coil is an aliquot part of the whole; and, as all the coils are fixed, the E.M.F. developed in any one coil can be easily measured,

and the gross E.M.F. deduced therefrom. As the range in a single coil is usually from 100 to 150 volts, an ordinary voltmeter can be used for the purpose, whereas, to measure the total potential difference directly, an electrostatic or other special voltmeter would be required. The machine is therefore fitted with a special pair of voltmeter terminals, connected to the ends of one coil, for the purpose of making this measurement.

It will be observed that the arrangement of the armature coils can, if required, be readily altered to vary the E.M.F. and current developed. For example, if it were required to reduce the E.M.F. of a 2,000-volt machine to 1,000 volts, this could be done by dividing the armature coils into two sets and joining them together in parallel, the machine being then capable of developing twice the current strength with the same density of current in the armature coils. Normally the larger machines are so connected with the armature coils in two sets joined in parallel, but the usual arrangement for the smaller sizes is with all the coils in series, in which case, of course, special attention must be paid to the insulation of the two adjacent coils at the terminals, since the maximum potential difference exists between them. In any case the total electrical output, or the energy developed, would be the same.

Fig. 144 represents the field-magnet of an early type of machine, the figure being retained because it illustrates the general principle more clearly than would a view of the latest pattern. In these earlier machines, copper dishes were attached outside the cast-iron claws of the field-magnets, for the purpose of reducing the amount of air-churning which would otherwise occasion loss of energy. The claws, in fig. 144, are shown without these dishes; in the newer form of the machine they are dispensed with, the claws being simply webbed together in the casting, when they present the appearance shown in fig. 142.

The field-magnet is excited by the current from a small Victoria direct current dynamo, which is mounted on a bracket projecting from the main bed-plate, its shaft being coupled direct to the alternator shaft, so that the two machines are driven together. A long thrust-bearing is employed to prevent end-play, which is an important point, since the space between the pole-faces and

armature is very small; and this bearing is adjustable longitudinally for the purpose of enabling the field-magnet to be symmetrically disposed with regard to the armature. The right-hand end of the shaft shown in fig. 144 fits into this bearing. The armature terminals are placed on the upper portion of the gun-metal supporting ring.

The machine illustrated, when driven at 500 revolutions per minute, is capable of developing 75,000 watts, or 100 electrical horse-power, at an E.M.F. of 2,000 volts. 900 watts are required for the purpose of exciting the field-magnets. On account of there being no iron in the armature, and the attention devoted to small details such as the use of German silver for the coil-fittings, the waste of power due to hysteresis and eddy currents is very small; and this loss, added to that due to friction, which, owing to good mechanical construction, is also very low, amounts to but 5 horse-power, that being the power required to drive the machine at full speed on open circuit (or when the armature is disconnected), the field-magnets being at the same time excited to their maximum.

In many cases the output demanded from a dynamo varies considerably at different times. For instance, four times as much power may be required to supply lamps at one time as at another. It is not economical to use one large machine, capable of meeting the maximum demand, and run it to give a small output at other times; but, fortunately, it is possible to join up two (or even more) alternating-current dynamos so as to feed the same circuit simultaneously when required, switching out and stopping one when the other is able to meet the low demand.

The armatures must not be joined up in series, but in parallel, and the machines may be driven by belts from the same shafting, or, if necessary, from independent engines running at about equal speeds. In practice the latter course is usually adopted, since it is uneconomical to employ a large engine to develop the power required by a small machine, which would be the case if two or more machines were driven from a common countershaft driven in its turn by a single large engine.

But parallel working is only practicable when in both machines the rates of alternation are equal, and the alternations 'co-phasal'

—that is, when their maximum and likewise their minimum E.M.F.'s occur simultaneously. It is most remarkable that well-designed machines can correct each other and maintain this synchronism; but, as a most important part of the interaction depends upon the 'motor' properties of a dynamo, further consideration of the question must be deferred until electric motors have been dealt with.

CHAPTER IX

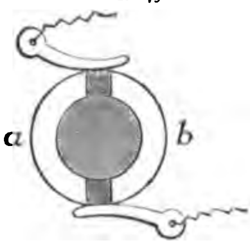
DYNAMO-ELECTRIC MACHINES (DIRECT CURRENT)

ALTHOUGH the sphere of usefulness for alternating-current dynamos has largely increased of late years, there is still a vast amount of work which such machines are, and always will be, wholly incompetent to perform. This is notably the case in connection with the deposition of metals by electricity, and in the 'charging' of secondary batteries. For these, and several other important purposes, it is essential that the current should be continuous, and flow in one direction only. Except in the case of a few experimental machines, the current which is generated in the armature always alternates in direction; but it is possible to arrange matters so that all the currents so generated shall be made to flow in one direction *in the external circuit*, the process being known as 'commutation,' and the part of the machine by which the alteration is effected is termed the 'commutator.' Directly this has been successfully performed, the dynamo is capable of a new and important development, for it is then possible to use all or a part of the current which is generated in the armature, for the purpose of magnetising the field-magnets. The smaller auxiliary machine, which, in most of the dynamos previously described, has been employed to excite the field-magnets, can therefore be dispensed with, and the machine made 'self-exciting.'

We come then to the consideration of the means to be employed in order that the currents which are generated in alternate directions in the armature itself can be commutated so as to flow in one direction *in the external circuit*. Referring again to fig. 127, we remember that the *direction* of the current is unaltered

(although it varies in E.M.F., and therefore also in strength) during the first half-revolution of the rectangle, and that, at the end of that half-revolution, the reversal in direction takes place. Now, a moment's reflection will show that if, just at the end of this first half-revolution, the positions of the two brushes on their respective rings were instantaneously interchanged, the current generated during the second half of the revolution would flow in the same direction round the external circuit as the preceding current did, because, although really generated in the reverse direction, it is entering the external circuit at the other end. This is the fundamental principle of commutation; only, instead of shifting the brushes, the change is effected at the right moment by a modification of the ring or rings against which the brushes press.

FIG. 145.



The simplest possible form of commutator is shown in section in fig. 145. Instead of two brass rings, a single brass ring or tube is employed, but with the difference that it is split lengthways into two halves or segments, *a b*, insulated one from the other. Each end of the rotating coil of wire is connected to one of these segments, and the brushes or flat springs (which are permanently connected one to each end of the external circuit) are so situated that they press upon the insulating divisions between the segments at the moment that the coil is in the vertical position—that is to say, in the position where the reversal of the current takes place. Just at that moment, then, the ends of the coil in contact with the respective brushes are also reversed, and the result is that when the coil is rotated uniformly, a succession of short currents passes through the external circuit, each current rising and falling similarly, but all impelled through the external circuit in the same direction.

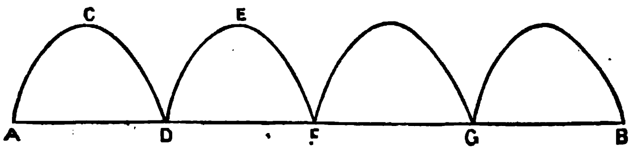
The length of the wire can easily be increased by winding it in a number of convolutions, instead of in a single rectangle, when, as a matter of course, the E.M.F. will be increased proportionately.

The variation in the E.M.F. developed by an ideal alternating-rent dynamo is shown in fig. 126, where the line A B represents

the normal or zero potential, the curves above it indicating the gradual rise and fall of, say, the positive potential, and those below it the opposite, or negative potential.

Fig. 146 exhibits, in a simple manner, the result of replacing the two metal rings by a split tube, or simple two-part commutator. A B again indicates the zero potential, and the curve A C D the varying potential developed during the first half-revolution; but, instead of the second half developing in the external circuit a negative potential, it is commutated into an external positive one, so that a series of currents, each of brief duration, is urged through the external circuit in one common direction. The total amount of current generated is, however, the same as before, although its strength oscillates rapidly between zero and the maximum.

FIG. 146.

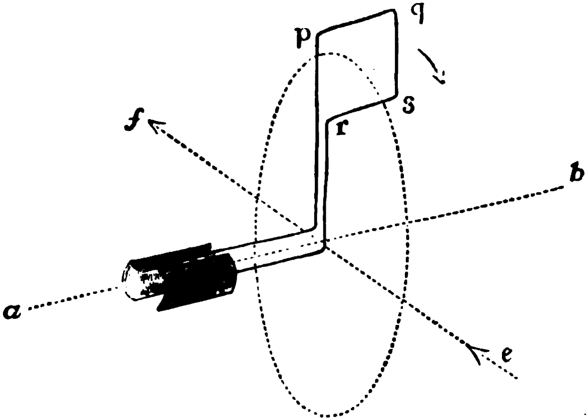


A current varying so much in strength is, however, of almost as little service for many purposes as an alternating current; for, in most cases, the current must not only be uniform in direction, but constant in strength. The methods by which an almost steady current can be obtained will be understood more easily when studied in connection with an armature constructed of coils wound on a somewhat different system. In fig. 147 *a b* indicates the axis of rotation, and *p q r s* a single loop of wire which travels round the circular path indicated by the dotted line, it being assumed that a uniform field is maintained throughout the whole of the space traversed by the wire. If we suppose the lines of force of the field to be in the direction of *e f*, along, or parallel to, a diameter of this circular path, then they will be cut by the coil in a manner somewhat similar to that of the rectangular coil which we have previously considered.

The movement from the vertical position through the first half-revolution produces a current which rises to a maximum when

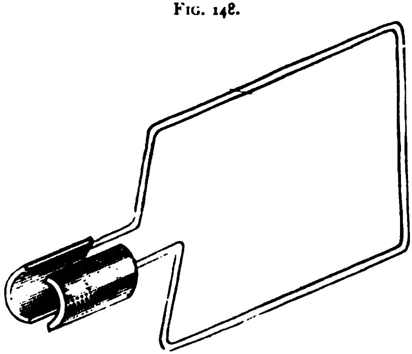
the coil has turned through an angle of 90°, and falls to zero again when the coil reaches 180°, while the current generated in the

FIG. 147.



next half-revolution is exactly equal in strength, at corresponding positions, though opposite in direction; but it can be commutated in precisely the same way as in the case of the ordinary rectangular coil, which is again illustrated in fig. 148. The ends of both these coils are shown connected to the metallic segments (equivalent to *a b* in fig. 145) of a simple two-part commutator.

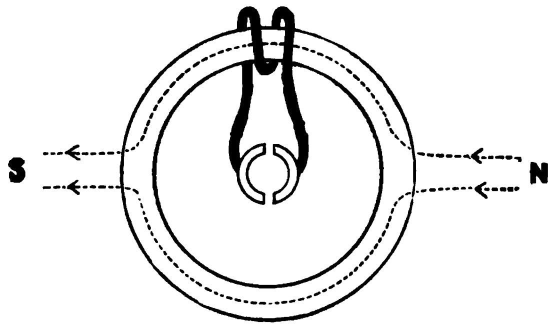
FIG. 148.



There is, however, one great difference between the two methods. No portion of the coil shown in fig. 148 acts prejudicially, although the portions connecting the horizontal limbs are always idle, inasmuch as they do not cut, but only slide through, the lines of force. With the coil shown in fig. 147 the case is

different. There are still two idle connecting lengths, $p\ r$ and $q\ s$, but the E.M.F. induced in the two horizontal limbs $p\ q$ and $r\ s$ is in the same direction in each—say from p to q and from r to s—because they always cut the lines in a similar sense, although at different rates; they therefore act in opposition to each other, each developing an E.M.F. which strives to set up a current in the opposite direction to the other round the coil. But the outer limb $p\ q$ traverses a greater portion of the field and moves at a greater linear velocity than does $r\ s$, and consequently, as it cuts more lines of force, and at a greater speed, than $r\ s$, the E.M.F. generated by it is the greater, the resulting current round the coil being therefore that due to the preponderance of the E.M.F.

FIG. 149.

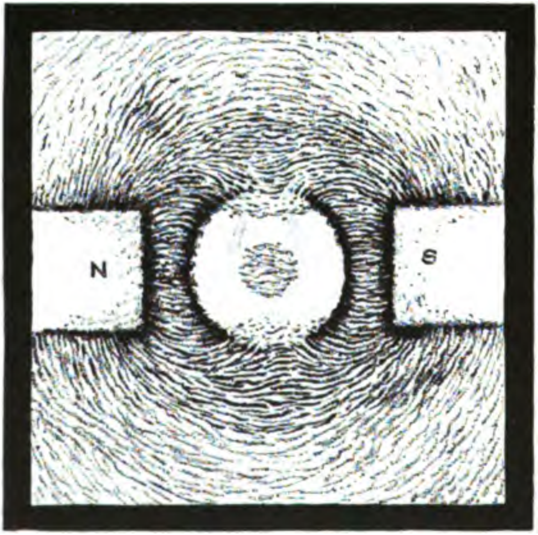


of the limb $p\ q$ over that of $r\ s$. Now, the lines of force which the outer limb cuts in excess of those cut by the inner limb are simply those which pass through the coil when it is in the zero position, as in fig. 147, and it is evident that if the field is uniform and the coil comparatively small the lines thus embraced will be very few indeed, and the use of iron to increase their number immediately suggests itself. It is most advantageous to make the iron in the form of a ring, as shown in fig. 149, and cause it to rotate with the coil. The coil here consists of two convolutions, and the dotted lines indicate the general direction of the lines of force through the iron when it is placed in the field between two opposite magnet poles. It must be clearly understood that in such a case

the lines of force will not rotate with the ring, but remain practically fixed in position, finding new points of entry and exit on the surface of the iron as the ring rotates.

The effect of so placing a ring of iron in a magnetic field is illustrated more precisely in fig. 150. The apparatus employed to obtain this figure consisted of a quantity of thin soft iron wire wound into a ring, and placed between the opposite poles of two powerful bar magnets, a sheet of paper being laid over the ring

FIG. 150.

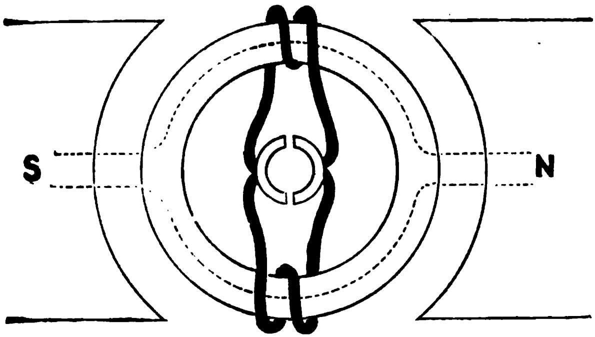


and magnet, and iron filings sprinkled upon it. The spaces free from filings represent those places where the permeability of the iron is sufficiently high to prevent any appreciable number of lines of force extending above the paper so as to give direction to the filings. The manner in which the lines converge into the ring should be noted, and it will also be observed that at two places, on a diameter at right angles with the lines, the magnetic effect above the paper is considerable. The reason for this is that the greatest number of lines pass through the iron at these

points, and the density of the lines here is so great that the permeability is sufficiently reduced to allow some lines to leak above the paper. Comparatively few lines pass diametrically across the interior of the ring, about half of them going through the upper and half through the lower part of it. Consequently the inner limb of the coil (fig. 149), if wound over and rotated with such a ring, would cut but very few lines, and the resulting E.M.F. would be practically that developed by the outer limb alone.

In the case illustrated in fig. 149 only one-half of the total number of lines of force urged through the iron can, at any one time, pass through the coil, and some device is therefore necessary to enable the other half to be utilised. Now, since the induced

FIG. 151.



E.M.F. will be the same in any given position after the coil has passed the point situated 180° from zero as it was in the corresponding position after it had passed the zero point, it is clear that a second coil might with advantage be placed at the opposite extremity of a diameter of the circular path described by the coil. We will assume that the limbs on the outer periphery alone are active, and it will be seen that if the induced current flows from front to back in the outer limb of the upper coil, it will flow from back to front in the outer limb of the lower coil, because these limbs always cut the lines from opposite sides, viz. one from above and the other from below. The E.M.F. is, however, at any moment equal in each, and, by joining the two ends which are at

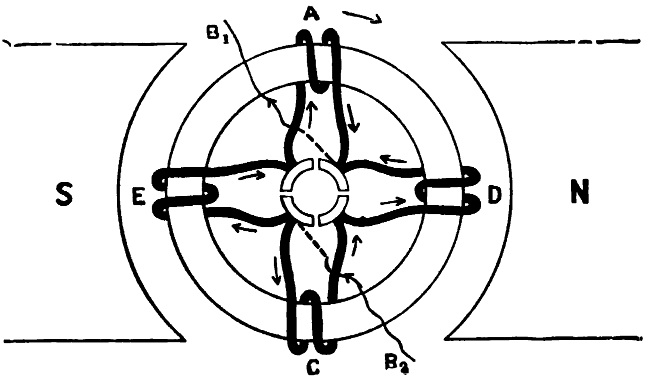
a positive potential to one segment and the two ends which are at a negative potential to the other segment, both coils are made to deliver their currents in the same direction to the external circuit.

Fig. 151 illustrates the arrangement for employing two such coils; they are similarly wound (right-handedly in this case), and their *adjacent* ends are joined to the same section of the commutator. Now, as they are at opposite extremities of a diameter, they pass at every moment through parts of the field where they act with equal effect, and therefore, as already pointed out, the E.M.F. will be the same at the extremities of each coil. Since the ends of the two coils, which are at the same E.M.F., are joined to the same segment of the commutator, the E.M.F. due to both coils is only the same as that produced by one of them, and the current will rise and fall in precisely the same manner as with a single coil. It is, in fact, an exactly analogous case to that of joining two primary cells of equal E.M.F. in parallel. There is also the corresponding advantage here that because the coils are joined in parallel the internal resistance between the two segments is only half that of one coil, and, as we have seen, any arrangement that so reduces the internal resistance of a current generator is sometimes very valuable. By increasing the number of turns in the coils we can increase the E.M.F., because a greater number of conductors in series, round the periphery, are then usefully cutting lines of force; but, of course, the number must be exactly the same in each coil. In figs. 149 and 151 it will be observed that there are two active conductors to each coil.

We are now in a position to proceed with the consideration of a method for making the short fluctuating currents depicted in fig. 146 approach more nearly to a continuous steady current. These short currents are at a minimum when the coils are at right angles to the lines of force, or at that point where the reversal of the induced current takes place, and it is evident that if a second pair of coils be placed at right angles to this existing pair, as in fig. 152, they will always lie parallel to the lines of force, or be in the position of best action, just at the moment when the first pair are almost idle. But it now becomes necessary to divide the commutator into four parts, all the coils being, of course, similarly

wound, and the adjacent ends of adjacent pairs connected to the same segment of the commutator. When only two segments are employed, the brushes, as we have observed, are placed so that the divisions of the commutator pass them just at the moment when the coils are at right angles to the lines of force, and when they are almost idle. In the present case, with four coils, the brushes must also be placed so that the division between each pair of segments on the commutator passes a brush when the coil connected to that pair of segments is in the position of least activity, viz. with its plane at right angles to the lines of force. We shall see presently that there are several causes which combine

FIG. 152.



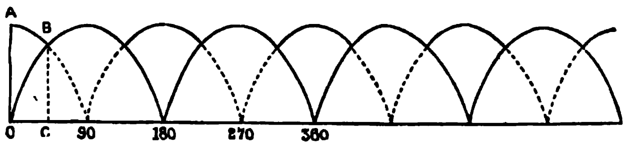
to slightly vary this particular position, although it can always be found.

In fig. 152 the brushes are indicated by dotted lines, and are shown slightly out of what we have hitherto considered to be their correct position. Supposing the lines of force to pass straight across from one pole-piece to the other, the currents in the various coils would flow in the direction indicated by the arrows, and the resulting current could be led from the armature to the external circuit by the upper brush B_1, entering the armature again by the lower brush B_2. The two horizontal coils D and E are in the position of greatest activity, while the vertical coils A and C are almost idle, and merely serve to conduct the current generated by the

active coils to that segment of the commutator which the brush is touching. A moment later A and C will each begin to generate a current in the opposite direction to the one now flowing in them, but as by that time they will have passed the brushes, their opposite ends will now be in contact with these same brushes, and the direction of the current in the external circuit will remain unaltered. When the plane of each of the four coils makes an angle of 45° with the lines of force, they are all equally active (although the activity of no one coil is so great as that of the coils E and D while they are in the best position, as shown in fig. 152), and the E.M.F. at the brushes is twice that which is at that moment being developed by one coil.

The resulting E.M.F., due to the joint effect of the double instead of the single pair of coils, is still far from constant, and, as

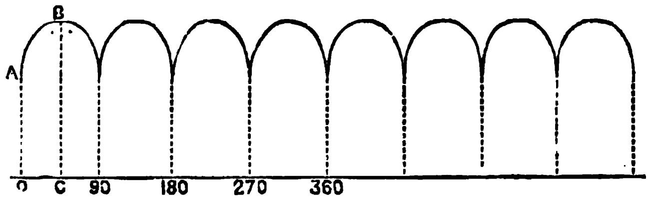
FIG. 153.



before, we must determine at what positions of the coils this resulting E.M.F. is at a maximum and where it becomes a minimum. The curve (fig. 146) illustrates the variation of the E.M.F. due to one coil or one pair of coils, and as, when this E.M.F. is highest, that of the second pair of coils is lowest, and *vice versâ*, the relative magnitude of the E.M.F. generated by two pairs of coils at different positions may be indicated by the overlapping curves in fig. 153. From this we wish to construct a curve which shall show how the E.M.F. *at the brushes* due to the effect of both pairs of coils varies. Now, twice during each revolution one of the two pairs is for the moment acting alone, and, consequently, the E.M.F. at the brushes is simply that due to this pair, and is proportional to the length of the perpendicular line O A. At this moment the E.M.F. at the brushes is at its lowest value, and the length of this line O A determines the lowest point on the curve which we desire to construct. Immediately after this point is passed both pairs are acting together, the activity of one increasing and that

of the other decreasing. At a certain stage they will be acting with exactly equal effect, and this stage is indicated by the intersection of the two curves in B; it occurs, as we have seen, at the moment when each coil makes an angle of 45° with the lines of force. To obtain, therefore, the resulting E.M.F. at the brushes, we must add together these two equal E.M.F.'s; consequently, twice the length of the line C B must be taken as the height of this the highest point in the new curve. When the coils have rotated through another 45°, one pair is again idle and the other at its maximum activity, so that we again reach the lowest point of the curve. The curve so constructed is shown in fig. 154, and it indicates the manner in which the total E.M.F. at the commutator brushes fluctuates when the armature consists of two pairs of coils arranged as in fig. 152. The resulting current will also fluctuate

FIG. 154.



similarly, depending in strength upon the gross resistance in the circuit.

It is obvious that the variation in the E.M.F. can be further diminished by the employment of a yet greater number of pairs of coils in the armature, provided that they are placed so that each pair comes into the position of best action at the moment when the resulting E.M.F., without their individual aid, would be at a minimum.

For instance, a coil might be placed exactly midway between each of those wound on the armature shown in fig. 152; that armature would then consist of eight coils in four pairs, and the commutator of eight bars or segments (fig. 155). The black portions of the circle represent the metallic segments, the white spaces between them indicating the insulating material. The current from such an armature would be far more steady than one

from the four-coil armature; in fact, it may be stated generally that the greater the number of coils composing the armature, the less the fluctuation of the current. Of course there is a practical limit to the number of coils; for instance, the commutator with this kind of armature must have as many segments as the armature has single coils or sections, and its construction and the making of the necessary connections would be difficult and expensive if the number were excessively increased.

It will be observed that in fig. 155 the whole armature conductor is wound continuously round the core; it is divided into sections having four convolutions each, and a connecting wire is led from the junction of every two adjacent sections to the proper segment of the commutator. The result is of course the same as if the ends of each section were brought direct to the commutator segment, while the actual length of the armature conductor, and therefore the resistance, is slightly reduced. In the following chapter several illustrations will be given of the way in which these commutator connections are effected in ordinary practice.

In order to increase the E.M.F. developed in a given field at a given speed, we must increase the number of conductors on the outer periphery of the armature, which can be done by adding to the number of convolutions, although this also increases the internal resistance. In the armature illustrated there are thirty-two active portions of the wire round the whole external periphery, but as they are joined up in two sets in parallel, the total E.M.F. is only sixteen times that of one active portion.

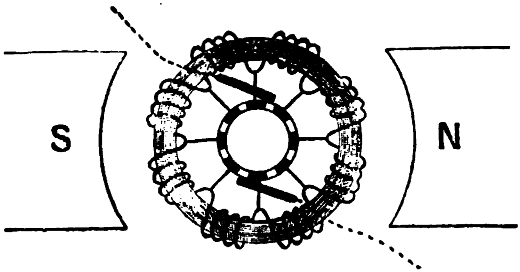
If we know the number of active conductors joined in series and the number of lines of force which they cut per second, it is easy to calculate the resulting E.M.F. The E.M.F. developed at any moment by any particular conductor moving circularly in a uniform field varies with its position, and is, as we have seen (Chapter VIII.), proportional to the cosine of the angle which the plane of the coil of which it forms a part makes with the lines of force; or to the sine of the angle through which the coil has turned from its position at right angles to the lines of force. But we need not now trouble ourselves with this consideration, for, in a symmetrically constructed armature of many convolutions, the place of each conductor as it moves to a position of greater or less activity is

immediately filled by another, and the total E.M.F. remains unaltered. Since each active length undergoes precisely the same inductive effects, the average E.M.F. induced in each is the same, and the total E.M.F. will be equal to the number of active conductors round one-half of the armature multiplied by the average E.M.F. developed by one of them during half a revolution.

Supposing the armature to consist of forty-eight convolutions and the average E.M.F. developed by one of the active limbs to be 2 volts, then the whole E.M.F. would be $2 \times 24 = 48$ volts.

The average E.M.F. developed by each active conductor depends upon the speed at which it moves, and the number of lines cut by it; in fact, we have seen that if a wire, one centimetre long, is moved at a velocity of one centimetre per second transversely

FIG. 155.



through a field of unit strength (that is, a field having one line of force per square centimetre), then the resulting E.M.F. will be equal to one C.G.S. unit. This unit being so very small, the volt is taken for practical use, having a value 10^8 or 100,000,000 times that of the C.G.S. unit. So that after calculating E.M.F. in C.G.S. units, the result must be divided by 10^8 to obtain the E.M.F. in volts.

It is preferable to consider the number of lines cut per second, which number can always be found, and then we need not know the length of the conductor or the intensity of the field in C.G.S. units, nor need any difficulty arise even if the field be not uniform. Referring again to fig. 155, suppose there are 16,000 lines of force forced through the armature core, these lines will all be cut twice

by each conductor during one complete revolution. If the armature makes one revolution per second, each conductor will cut 32,000 lines per second and generate an average electro-motive force of 32,000 C.G.S. units. And as there are sixteen conductors in series, the total average E.M.F. as measured at the brushes will be $16 \times 32{,}000 = 512{,}000$ C.G.S. units, or

$$\frac{512{,}000}{10^8} = \cdot 005 \text{ volt nearly.}$$

If the armature made ten revolutions per second, the E.M.F. would be ten times greater (i.e. 0·05 volt), because each conductor would now cut ten times the number of lines per second.

In fact, we may say that the average E.M.F. generated in an armature of this description is equal to

$$\text{N} \times \frac{\text{P}}{2} \times 2n, \text{ that is, N P } n \text{ C.G.S. units,}$$

or

$$\text{average E} = \frac{\text{N P } n}{10^8} \text{ volts,}$$

where N is the total number of lines of force urged through the armature core; P the total number of active conductors lying round the periphery, and $\frac{\text{P}}{2}$, therefore, the number in series; n the number of revolutions per second, and $2n$, therefore, the number of times per second which the whole of the lines are cut by each conductor.

The E.M.F. obtained in the last example (0·05 volt) is very low, because we assumed a rather low speed and few lines of force. In practice it is not unusual to force several millions of lines through the armature core. Supposing the number to be 3,000,000, and the number of conductors round the periphery to be 150, then if the armature is driven at 1,200 revolutions per minute, or 20 per second, the E.M.F. developed would be

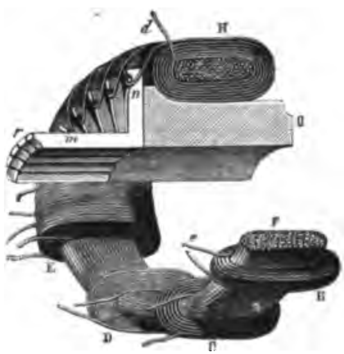
$$\frac{3{,}000{,}000 \times 150 \times 20}{100{,}000{,}000} = 90 \text{ volts.}$$

The above is a fair example of what obtains in actual practice, and the student will readily perceive that it is necessary for the quantity of iron in the armature core to be considerable, otherwise

with such a large number of lines of force the magnetic induction through it (that is, the number of lines per square centimetre) would be abnormally high. We know that the permeability of iron decreases rapidly when the induction through it exceeds a certain amount, and then a large number of the lines leak diametrically across the ring instead of taking the path indicated in fig. 151, many of them passing across the steel driving shaft, the permeability of which may be equal to that of the 'saturated' iron.

Now, as these lines of force thus leaking across the ring are cut by the inner portions of the conductor (equivalent to *r s* in fig. 147) and act prejudicially, inasmuch as the E.M.F. generated by the inner wires in cutting them is reverse to the main E.M.F., it is evidently inadvisable for this reason, if for no other, to endeavour to push the induction too far. As a rule the limit is from 16,000 to 18,000 lines per square centimetre, and if more lines through the core are needed, either the area must be increased or iron of higher permeability employed. The former necessarily entails a greater length of conductor. It is evident that in an armature of the type we are considering, the iron of which the core is made should be of the highest possible permeability, while the quantity of iron or steel used inside the ring should be as small as possible to minimise the tendency to cross-leakage. This latter consideration implies that iron should not be employed for the purpose of mechanically connecting the ring to the driving shaft. In practice, gun-metal or some other non-magnetic alloy is used.

FIG. 156.



The first armature on this principle was constructed by Pacinotti, but it remained unnoticed until the essential features had been combined in a slightly different form by Gramme.

Fig. 156 illustrates the construction of an early form of Gramme armature, the core being shown cut through, and some of the coils

displaced to make it clearer. The core, F, consists of a quantity of iron wire wound continuously to form a ring of the shape shown by the section. Over this is wound about thirty coils of insulated copper wire, B C D, &c., the direction of the winding of each being the same, and their adjacent ends connected together. The commutator segments consist of a corresponding number of brass angle-pieces, *m n*, which are fixed against the wooden boss, *o*, carried on the driving shaft.

The junction of every two adjacent coils is connected to one of the commutator segments, as shown, and in the completed machine two flat brushes of copper wire would be pressed against the projecting ends of the segments, and serve to deliver the current to the external circuit. The latest forms of this armature, although identical in principle, are far superior from a mechanical point of view; in fact, the armature here illustrated would fly to pieces if subjected to the stresses which occur in a modern machine.

It is necessary that the commutator bars should be firmly held in position, that the wire should be bound or by some means fixed so as to prevent its being shifted, and that the core and with it the coils should be firmly secured to the driving shaft. As far as possible it will be shown, in describing the best types of machines, how these points are attended to in practice. Especial care must be taken to prevent the generation of eddy currents in the core, and this was Gramme's reason for using rather fine wire instead of a solid ring. We have previously remarked that the E.M.F. which gives rise to these eddy currents is very low (although the current strength may be considerable, because the large mass of metal involved offers little resistance), and that, therefore, the merest film of insulation between neighbouring wires of the core is sufficient. Except in special cases a coating of shellac varnish, or even a coating of rust, is all that is required, and it should be borne in mind that the space occupied by insulation should always be as small as possible, so as to allow the maximum amount of iron to be used in a given space. If the armature is rotated in a simple field between two pole-pieces, it is not necessary to subdivide the core to the extent adopted in the earlier Gramme machines, for since the direction of the eddy

currents is at right angles to the lines of force and to the direction in which the core moves, there will be no tendency for them to flow in a radial direction, but only along lines parallel to the driving shaft. Therefore the core may be simply laminated, or built up of a number of thin discs of soft iron, thus giving better facilities for mechanical connection with the shaft, and also reducing the magnetic resistance considerably. In entering or leaving the interior of the wire core, the lines of force have to leap across numerous little spaces of low permeability, while in the case of a core built up of discs, not only is the mass of iron greater, but it is also continuous in the direction of the lines, and discontinuous only in the path which would be taken by the eddy currents.

Returning now to a consideration of the phenomena developed by the actual rotation of the armature, we may repeat that the brushes must be so placed that every division between the segments of the commutator passes under a brush just at that moment when the coil, the ends of which are connected to those segments, is idle. Now this happens when the plane of the coil is at right angles to the lines of force, so that if the lines of force always retained their regular straight direction between the poles of the field magnet, or even if they curved regularly through the iron core as indicated in fig. 151, it would be easy to fix the correct position for the brushes. But, unfortunately, the field is considerably distorted immediately the armature is caused to rotate and the current established. This distortion is due to the fact that the armature itself becomes a powerful electro-magnet, having lines of force which are not coincident with those of the field magnets.

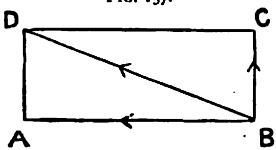
The two halves of the core are, as a matter of fact, magnetised by the currents passing round them, and in such a manner that their similar poles are adjacent to each other and situated at the points where the two currents enter and leave the external circuit. Now, if two semicircular magnets of equal strength are placed so as to form a circle with their *unlike* poles adjacent, they form a complete closed magnetic circuit, nearly all the lines of force taking the path of the iron or steel, and there is consequently very little external magnetic effect observable. But if these same semi-

circular magnets are placed with their *like* poles adjacent, there is abundant external evidence of the magnetic strength of the combination. The circle acts, indeed, as if it were a single magnet, the distance between its poles being the length of the diameter. Some of the lines of force find their way back across the diameter to the opposite pole, while others pass round outside the circle, a much larger proportion taking this course when, as in the case of a dynamo, there are large masses of iron in the vicinity.

The position of the brushes determines the position of the poles of the armature, since they form the meeting points for the currents in the two halves of the armature, and when the brushes are placed on a diameter at right angles to the lines of force of the field, these poles are also at right angles to those lines of force.

It is manifest that as the tendency is for the armature to generate a magnetic field in one direction, while the field magnets strive to maintain one in another, the direction of the resultant field must lie between the two, the exact position depending to a great extent upon the relative magnetising forces of the armature and field magnets. Were these relative forces known, the direction of the field might be determined approximately by the well-known 'parallelogram of forces' (see fig. 157). In this case the line A B represents by its position the direction, and by its length the magnitude, of the magnetising force due to the field magnets alone, while the line B C, drawn at right angles to A B, represents the direction and force of the field due to the armature. Then the diagonal B D of the completed parallelogram represents both in magnitude and direction the resulting magnetic field. Now the brushes must be set on a diameter at right angles to these resulting lines of force. Hence this shifting of the field due to the reaction of the armature necessitates also the shifting of the brushes through a corresponding angle, equal, in fact, to the angle D B A.

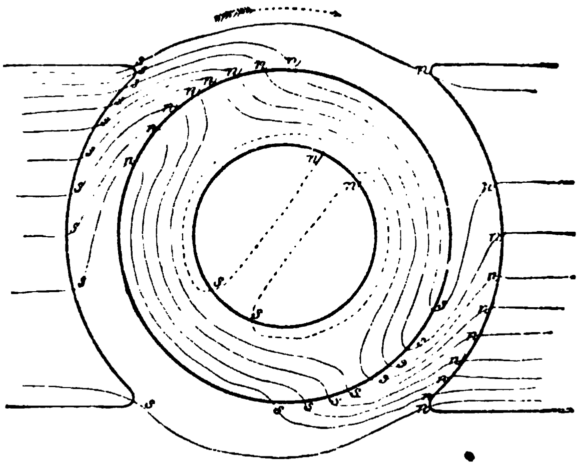
FIG. 157.



This altered position of the brushes is commonly known as the *lead* given to them, and the angle through which they are

moved is known as the angle of lead. In every dynamo the lead is forward, or in the direction of the rotation of the armature. But the parallelogram of forces referred to above does not exactly indicate the true angle, because immediately a lead is given to the brushes the polarity of the armature is shifted through a corresponding angle, the result being to still further distort the field and again increase the angle of lead. It will be evident that if we wish to reduce the angle D B A (fig. 157), it can be done by decreasing B C or increasing A B, which in either case would result from making the magnetising force of the field magnets

FIG. 158.



great as compared with that of the armature. Practice also dictates, for this and for other reasons, that the magnetic field in which the armature revolves should be as strong as possible, and always very much stronger than that developed by the armature itself. In fig. 158 is illustrated the direction of the resultant field of a dynamo when the armature is revolving in the direction indicated by the arrow, and is generating a current. It will be observed that the lines of force, *ns*, *ns*, are considerably distorted or dragged out of their normal position, and that this distortion takes place in the direction of rotation. The lines which cross

the space inside the armature ring indicate the direction of leakage.

When the external resistance through which a dynamo is working is varied, the current in the armature, and therefore the field produced by it, also varies; the same cause may also alter the field produced by the field magnets if the machine is 'self-exciting,' and consequently in practice the angle of lead sometimes varies considerably. If the effective fields produced by the field-magnets and the armature were varied in the same proportion, the angle of lead would remain constant; but we shall see presently that because (among other things) the induction through and the permeability of the field-magnet and armature cores do not vary together, this proportion is not maintained, although the currents producing those fields may be equally increased or diminished. Too much stress cannot be laid upon the necessity for setting the brushes in the proper position, and to facilitate matters they are usually mounted on an insulating rocker so that they may be shifted together through a considerable angle until the correct position is found.

When the field is a simple one, such as that between the two poles of a magnet, and providing it is also uniform, the brushes are placed at opposite extremities of a diameter of the commutator, no matter what the angle of lead may be.

When the brushes are not properly adjusted, the coils are short-circuited while they are more or less active, and considerable sparking occurs at the commutator, injuring that important part of the machine, and giving evidence of wasted energy.

Practically the best position of the brushes can be found by shifting them while the machine is running (the external circuit being at the time completed) until there is very little or no sparking observable; and it is found that they must be set even a little further ahead than the point where they are at right angles to the direction of the resultant lines of force. This slight extra lead is necessitated by the rather peculiar and important action which takes place in a coil as it passes a brush. The brush has a sufficiently wide bearing on the commutator to bridge over the interval between the two segments and so to short-circuit the coil attached to them, for a brief interval of time; and although this

may take place when the coil is in itself, as a generating coil, almost inactive, it must be remembered that it has considerable self-induction, consisting as it does of a number of convolutions of wire wrapped round a comparatively large mass of soft iron. We have considered at length the reasons which prevent a current being suddenly started or stopped in any circuit which has an appreciable amount of self-induction, from which it is evident that, although the coil itself may not be actually generating any current, yet it is carrying the whole of the current generated by the other coils in the same half of the ring, and when short-circuited by the brush this current will not immediately die out, but will become even stronger for a moment and then expire. Independently of this it is impossible in practice to attain the theoretical condition of each coil being absolutely idle even for the briefest possible interval during which the coil might be short-circuited; and although the E.M.F. generated when the coil is least active may be very small, yet the resistance is as a rule so extremely low, being but a small fraction of an ohm, that the current strength when the coil is short-circuited becomes perforce considerable. The energy of currents so circulating round the coils while they are in turn short-circuited, is expended in heating the wire, and this effect must be remembered as one of the many causes which necessitate special attention being paid to ventilation in designing a dynamo armature. Ventilation does not of course prevent the generation of heat and consequent waste of energy, but it facilitates dissipation and thereby tends to keep the temperature from rising to a dangerous point.

To ensure the entire stoppage of the current, and also even to allow sufficient time for a current in the opposite direction to be just started in the coil before it is actually thrown into circuit again in the other half of the armature, it is advantageous to have the brushes rather thick and to give them the slight extra lead above referred to.

But much can be done to reduce the angle of lead, and minimise sparking, by making the field very strong, and constructing the armature with many sections, each of few convolutions. Further, although it involves an increase in the magnetic resistance, and therefore necessitates an increase in the magneto-motive force

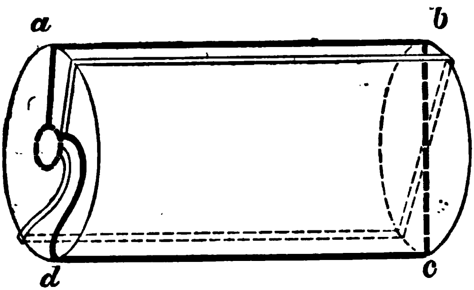
developed by the field-magnet coils, it is distinctly advantageous, so far as the reduction of sparking is concerned, to design a machine so that the value of B, or the intensity of magnetisation in the armature core, shall be considerable, because then the permeability of the iron becomes considerably reduced, and the self-induction of any one coil is much less than it would be if wound over a similar mass of more feebly magnetised iron. In many machines each section consists of but one convolution, and the brushes can easily be adjusted so that absolutely no sparking can be observed, while, the field-magnets being very powerful, the angle of lead is very small, even when the armature is carrying its maximum current. In such a case the armature current may vary considerably without necessitating any readjustment of the brushes, such as becomes necessary with badly designed machines, in which the brushes have to be rocked forward directly the armature current increases slightly in strength, and backward when it is diminished.

It will be remembered that we commenced the study of the direct-current dynamo with the aid of a simple rectangular coil (fig. 123), but that subsequently, to make the development of the subject easier, a different system of winding was introduced, leading up to the Gramme armature. We are now in a position to comprehend more readily the manner in which excellent armatures, commonly known as 'drum' armatures, are constructed upon the principle of the rectangular coil first mentioned. The drum armature is really a natural development of the shuttle armature so much used in small magneto machines. This shuttle armature, consisting, as it does, of only one coil of many turns, the ends of the coil being joined one to each segment of a simple two-part commutator, gives a current fluctuating from maximum to zero twice in each revolution, and greater steadiness was aimed at and obtained by placing a number of coils symmetrically round the core; in just the same way that a considerable number of coils wound on the Gramme principle yield a more nearly constant current than would result from a single coil or a pair of coils. A drum armature is somewhat more difficult to construct and to illustrate, and although the fundamental principle is in all cases that just indicated, there are many ways of making the necessary

connections, some of which will be described when dealing with actual machines.

The general principle may be gathered from fig. 159, where only two adjacent sections are shown, each having one turn. The core is shaped like a cylinder, or drum; a commutator, similar to those already described, being mounted at one end of the shaft. From one segment the first coil ascends up the face of the drum to *a*, thence lengthways along the cylinder to *b*, whence it passes across a diameter to *c*, and along the length of the cylinder to *d*. From *d* it is brought round the face and connected to the segment next to that one to which the other end of the coil is joined. The second coil, shown by open lines for distinction, starts from the segment at which the first coil terminates, and is

FIG. 159.



wound similarly to that coil, being placed a little further round the drum as shown. Its two ends also are connected to adjacent segments, and, in a similar manner, coils would be placed all round the cylinder, equidistant, and with the ends of each joined to two adjacent commutator segments, so that every segment has two wires connected to it. Many of the best drum armatures are constructed with but one convolution in each section, but when it is desired to increase this number the wire is simply wound the requisite number of times round the cylinder, and the end of the last convolution led from the point *d* to the commutator segment. Of course, the wires cannot be brought diametrically across the face, as shown at *b c*, on account of the driving-shaft, and when there are several convolutions in each section care is taken to place an

equal number of the wires on either side of the shaft, so as to preserve a mechanical as well as an electrical balance. In any case, great care has to be taken with these cross-connections, which are, in fact, a serious source of trouble, for, since portions of all the coils overlap here, it is possible to get wires having a high potential difference very close together. This difficulty does not arise with a Gramme ring.

The great advantage peculiar to a drum armature is the fact that the conductors usefully cut *all* the lines of force passing through the armature core. The only idle wire is that used for connections across the ends of the cylinder; and no part of the conductor can generate an E.M.F. in the counter-direction. Consequently, iron may be employed for all the internal fittings; in fact, but for the necessity of allowing space for ventilation, the whole of the inside of the armature might be occupied by iron. Since the active limbs, *a b*, *c d*, always cut the lines of the field from opposite sides—viz. one from above, the other from below—the current is induced from front to back in one and from back to front in the other, so that it circulates in the same direction round the coil, precisely as in the case of the simple rectangle first considered.

Each coil is equivalent, then, to two diametrically opposite coils in a Gramme armature, and there will be as many commutator segments as there are coils. The reversal of the current takes place, of course, as each coil passes the zero position—viz. with its plane at right angles to the lines of force—and it is in this position that the segments to which it is connected pass the brush. Also, as in the case of the Gramme ring, the resistance from brush to brush, through two halves of the armature in parallel, is only one quarter of that of the whole armature in series, and, in calculating E.M.F., the formula, $E = \frac{N P n}{10^8}$, holds good, P being the number of active conductors, such as *a b*, round the periphery of the drum.

The drum armature is more efficient than any other form, and we may briefly compare the relative advantages of the drum and ring type by supposing that we have two armatures of equal diameter, and having active conductors arranged round them equal in

number and length. The magnetic resistance offered by the drum armature will be the smaller, because the quantity of iron in its core is greater, and therefore a given magneto-motive force can urge more lines of force through it than through the ring armature. Further, the whole of the lines passing through the drum armature are usefully cut by the conductors, while, in the case of the ring, some leak across to the shaft and are cut by the inner portions of the wire in such a manner as to reduce the main E.M.F. Therefore, with a given magneto-motive force to maintain the field, the drum armature will give a higher E.M.F. than the ring when they are driven at equal speeds. Equal E.M.F.'s might be obtained by reducing N, the number of lines of force, or P, the number of active conductors; but the factor which it is usually sought to keep as low as possible is n, the number of revolutions per second. One great practical advantage of a drum armature is that it enables slow-speed machines of comparatively moderate proportions to be constructed, and it will be observed that few slow-speed dynamos have ring armatures; indeed, few simple ring armatures are now used except for the generation of comparatively small currents. Since the proportion of idle wire is slightly less in the drum than in the ring type, its conductor resistance for the same weight of copper is rather lower, while, on the other hand, it has the disadvantages that it is difficult to make it as strong mechanically as the ring, the cross-connections are somewhat troublesome, and, as a rule, special arrangements are needed to ensure sufficient ventilation.

Having discussed some of the theoretical points involved in the construction and action of direct-current dynamo armatures, we will now consider the methods of maintaining the field, which, it will be remembered, must be as strong as possible. As in the case of the more powerful of the machines described in the preceding chapter, electro-magnets (called the field-magnets) are employed for this purpose. Practical difficulties and economy in construction somewhat influence the shape, but in every case the great object should be borne in mind, viz. the necessity for leading as many lines of force as possible through the space between the poles, in which the armature is made to revolve.

The magneto-motive force, which sets up the lines of force, is

obtained by means of a current passing through one or more coils of wire, and is proportional to the strength of the current flowing and the number of turns of wire in the coil, as has already been fully explained (Chapter VII.), and the quantity represented by the product of these two factors is referred to as the 'ampere-turns.'

Now, for any given machine, the number of lines of force which must be urged through the armature is usually determined beforehand, but as with every electro-magnet, of whatever design, there is a certain amount of 'leakage,' only a portion of the lines generated by the field magnet pass through the armature.

But power is expended in the generation and maintenance of the lines of force, and those which are rendered useless by leakage represent so much power wasted. It is obviously advisable that this waste should be reduced to a minimum, and the greatest possible proportion of the lines developed led through the armature. This may be accomplished by making the magnetic resistance of the desired path very low. The whole magnetic circuit should, preferably, approximate to the circular form, and whatever the quality of the iron employed, its sectional area must be sufficient at every point to prevent the magnetic induction being so high as to very greatly reduce the permeability of the iron. We have mentioned one advantage which results from working the armature core at a rather high induction, but in doing this we cannot, of course, avoid correspondingly increasing the magnetic resistance of the circuit.

The spaces between the pole-pieces of the field-magnet and the core of the armature offer considerable magnetic resistance, which may be taken as proportional to the distance between the iron surfaces, the permeability of the copper wire and its insulation being about the same as that of air. The only way of diminishing this high resistance is to reduce the distance between the iron surfaces as much as safety will permit, and, since this minimum distance is nearly the same in machines of all sizes, we see one reason to account for the observed fact that small dynamos are generally less efficient than larger ones.

In estimating the tendency to leakage it must not be forgotten that while the permeability of iron decreases with an increase of the magnetic induction through it, that of air remains constant,

and the difference between the permeability of the nearly saturated iron of the field-magnets, and that of the air space, is never anything like the difference usually given for unsaturated soft iron and air.

Two very important considerations influencing the design of field-magnets are economy in construction and mechanical strength; and in practice, as we shall see, it is sometimes considered advisable, where the question of weight is unimportant, to use cast-iron for part or all of the field-magnet core. It is preferable to forge or cast the core in one piece, as joints break the molecular continuity and increase the magnetic resistance considerably, although this disadvantage can be minimised by making the surfaces in contact fit truly. The principal practical objection to the use of cast-iron is that, since its sectional area must be at least twice that of wrought-iron, a much greater quantity of copper is required to form the field-magnet coils. Copper is expensive, while cast-iron cores are far less costly than equivalent ones of wrought-iron, and the student should observe how different makers aim at true economy in this matter. Even leaving out the question of cost and weight, it does not by any means follow (as is sometimes supposed) that a dynamo properly designed to perform certain work, and having cast-iron in its construction, is inferior to one built wholly of wrought-iron to perform the same work. Steel has recently been employed in some cases instead of wrought-iron for field-magnet cores, the principal advantage in its favour being that it can be cast into the desired shape, thus avoiding the somewhat expensive processes of forging and machining up to shape, which are necessary in the case of wrought-iron. It must be remembered, however, that ordinary hard tool-steel is unsuitable for this purpose, the metal employed being mild steel, which contains very little carbon, and cannot be hardened or tempered, and the most suitable qualities of which, when carefully annealed, are scarcely inferior to wrought-iron as regards permeability.

The composition of the 'ampere-turns'—that is, the proportion of current strength to the number of convolutions—will depend largely upon the manner in which the exciting current is obtained; for it is sometimes necessary to have considerable resistance in the coils, and then the number of convolutions may

be made great and the current correspondingly weak; while in other cases a high resistance is inadmissible, when only a few turns can be employed, and the necessary magneto-motive force must then be obtained by the aid of a heavy current.

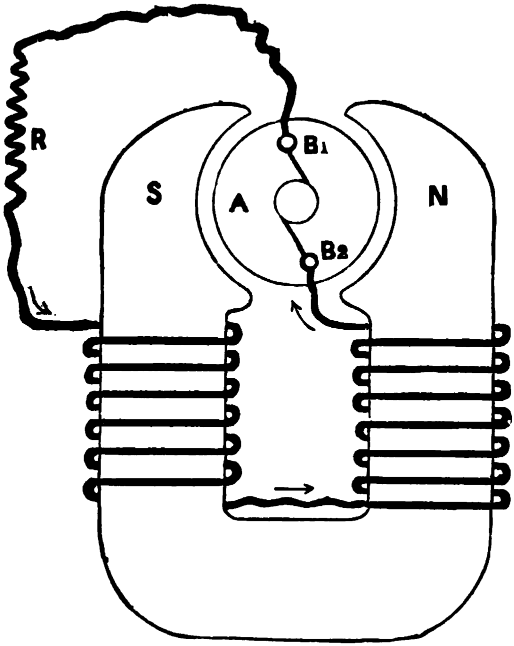
At the beginning of this chapter we referred to a very important benefit following the commutation of the current, viz. the possibility of using all or part of the current generated in the armature, for the purpose of magnetising the field-magnets, and the simplest method of doing this, in which the whole of the current is so employed, is exemplified in fig. 160. A machine having its connections made in the manner there shown is known as a 'Series' dynamo.

S N are the pole-pieces of a massive horse-shoe electro-magnet; the armature A revolves in the space between them, B_1 B_2 being the brushes which press against the commutator, and by means of which the current generated in the armature can be led to any desired point. In this case, one end of the wire forming the coil of the electro-magnet is connected directly to the brush B_2, the other end being joined through the external circuit R to the opposite brush B_1, so that the circuit of the field-magnet is completed through the armature coils. Hence the whole of the current generated in the armature must pass round the coils and magnetise the electro-magnet.

But how is the current to be started in the first instance? It so happens that even the purest soft iron is found to retain some of the magnetism imparted to it, and therefore the massive cores of a dynamo, having once been strongly magnetised, always retain an appreciable amount. This 'residual' magnetism is sufficient to project a few lines of force through the armature coils; so that, when the armature is rotated, a feeble current is generated in them. The connections being made as in fig. 160, this current leaves the armature by the top brush B_1, flows through the external circuit, and, returning to the machine, passes round the coils of the field-magnets, the circuit being completed through the lower brush B_2. The feeble current sent in this way through the field-magnets increases the strength of the field in which the armature rotates, and, consequently, the current generated also becomes stronger. This further increases the magnetic field developed, and, conse-

quently, also the current strength; action and reaction succeeding one another, until presently the current becomes very strong indeed. This increase does not, however, continue indefinitely, there being two especially important restrictions which tend to fix a limit to the current produced. In the first place, although the core of the field-magnet may be very massive, its magnetisation eventually

FIG. 160.



approaches the saturation-point, beyond which an increase of the current in the coils would not by any means involve a corresponding increase in the strength of the effective field. Secondly, the rotation of the armature, although performed with little effort at the commencement, requires a considerable expenditure of energy as the strength of the current increases. We are even able to estimate the relative amounts of the power required to turn the armature

while currents of different strengths are being generated. For our present purpose the calculation can be made very simple by ignoring the power lost in mechanical friction, &c. The electrical power which is being developed in any circuit can be found by simply multiplying together the electro-motive force in volts and the current strength in amperes in that circuit, the result being the number of watts of power developed therein, or $W = E \times C$, W being the number of watts.

As the E.M.F. is equal to the product of current strength and resistance (that is, $E = C \times R$), we may write $W = (C \times R) \times C = C^2 \times R$; that is to say, the power in watts developed is equal to the resistance in ohms multiplied by the square of the current strength in amperes.

As the resistance of the dynamo armature and magnet coils is always known, only one measurement, that of current strength, need be taken, which can be done by any ammeter of negligibly low resistance.

Supposing, for example, the resistance of the armature to be 3 ohms, and that of the field-magnets to be 2 ohms, then the total resistance is 5 ohms. When a current of 10 amperes is generated without any external resistance, the electrical power appearing in the circuit is equal to $C^2R = 100 \times 5 = 500$ watts; and if the current is increased to 20 amperes, then $C^2R = 400 \times 5 = 2{,}000$ watts.

Now, in both cases at least as much mechanical power is required to turn the armature as appears in the circuit as electrical power. Indeed, a certain amount in excess is necessary (depending upon the efficiency of the machine), because some energy must be wasted in overcoming the mechanical friction of the bearings, &c., and still more by various electrical causes, such as eddy currents and the currents which flow in the armature coils during the period of short-circuiting.

The main point, however, upon which we desire at present to lay stress is that the increase in the current is not, and never can be, obtained without a corresponding increase in the power expended in turning the armature; in fact, from the above reasoning it is clear that in a series dynamo such as the one described, the mechanical power expended varies as the *square* of the strength of

the current obtained in the external circuit, always supposing the resistance of the circuit to remain constant, and ignoring the mechanical power lost in the machine during conversion.

The ultimate strength of the current is, then, limited not only by the saturation of the field-magnets, but also by the amount of power at our disposal to drive the armature round. The engine, or other source from which the power is derived, must at least be able to furnish power equal to the maximum electrical power it is desired to obtain, to which must also be added that which is wasted or lost in the conversion. A yet further limit is imposed by the capacity of the conductors for carrying heavy currents.

With regard to the residual magnetism which is relied upon to start the current, it may be remarked that if the field-magnets are once strongly magnetised by a current passing in the direction in which it is desired the currents shall afterwards be generated, the cores will rarely lose all traces of magnetism, especially if of cast-iron. This sometimes happens, however, when the dynamo is moved, and the magnetism may even be reversed; but matters can easily be righted by passing a current, say, from a few cells for a moment in the proper direction through the field-magnet coils.

Hitherto, the dynamo has been considered as only working on 'short circuit'—that is, with the circuit completed without the introduction of any appreciable external resistance. In practice, we require the current to do a greater or less amount of work in an external circuit, such as developing light in electric lamps or driving an electro-motor. In such a case, part only of the power is expended in overcoming the internal resistance (that is, the resistance of the armature and field-magnets) and maintaining the field, the remainder being employed in the external circuit. It is easy to find the relative amount of power absorbed in the two parts of the circuit. Thus, suppose the strength of the current to be 40 amperes, and the total E.M.F. to be 80 volts, then the total electrical power developed is $40 \times 80 = 3{,}200$ watts. If, now, the difference of potential between the two extremities of the external circuit is found to be 60 volts, the power absorbed therein is $40 \times 60 = 2{,}400$ watts, for the strength of the current is the same in all parts of the same circuit. The remaining difference of potential is $80 - 60 = 20$ volts, which is the fall along the

internal circuit, and which absorbs, therefore, $40 \times 20 = 800$ watts. In this way, the ratio between the power spent in the external and internal portions of the circuit can in every case be measured. The two ends of the external circuit above referred to are connected to the 'dynamo terminals,' and the potential difference thereat can be measured by any convenient voltmeter. Since, also, the power spent in either portion can be calculated by multiplying the square of the current strength by the resistance of that portion of the circuit, and as the current is the same in each part, it follows that the energy absorbed in either part is directly proportional to the resistance of that part. Thus, if the resistance of the external circuit is R ohms, and that of the dynamo r ohms, the total resistance is $R+r$. Let the total number of watts developed be W. Then, denoting the watts absorbed in the internal and external parts of the circuit by x and y respectively, we have

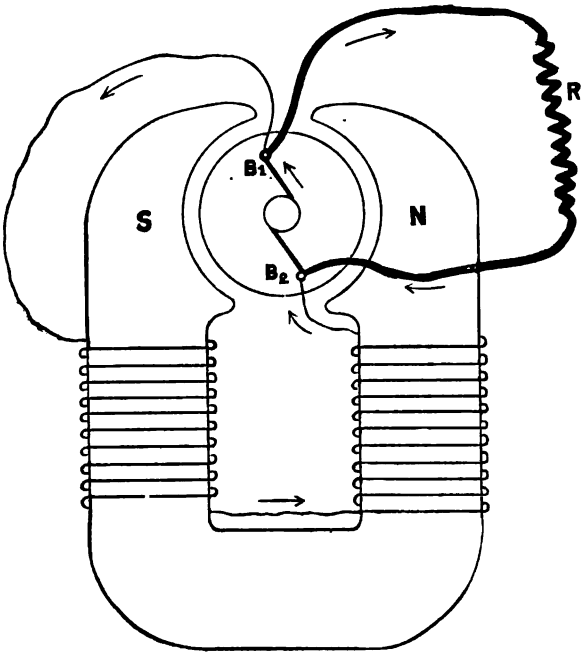
$$x : y :: r : R,$$
$$x : W :: r : R+r,$$
$$y : W :: R : R+r.$$

But it is very rarely that any dynamo works through an external circuit of constant resistance; if it is supplying current to electric lamps, some of them are liable to be thrown into or out of circuit at any moment, and the behaviour of a series dynamo under these varying conditions must be briefly noted. Supposing the lamps to be joined up in series, then any addition to the number will increase the external resistance and reduce the current strength, and this means a corresponding decrease in the strength of the field, and, consequently, a further diminution in the current strength. If we suppose the lamps to be joined up in parallel, then any addition to the number in circuit decreases the total resistance and increases the current. This, by strengthening the field, still further increases the current strength. So that in either case considerable difficulties arise when a series dynamo is used on a circuit of varying resistance.

Moreover, this variation of the current, while it varies the effective fields of the armature and field-magnet, does not do so in the same proportion. The angle of lead must therefore be

altered for every alteration of the current, or injurious sparking at the brushes will ensue. A series dynamo can be used most conveniently in cases where a current of constant strength is required, and then if the resistance of the circuit remains constant the current also remains constant, provided the dynamo be driven at a regular speed. Should the resistance of the external circuit

FIG. 161.



vary from time to time, the current can still be kept constant by providing an arrangement to automatically vary the strength of the field in which the armature rotates. For example, the field-magnet coil may be shunted by a resistance whose value can be reduced, and so shunt a larger proportion of the current from the field-magnet coils, whenever the current in the main circuit tends to rise above the standard strength; and increased so as

to shunt less current when the main current falls below its proper value.

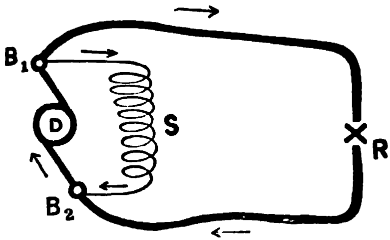
It will be evident, however, that the conditions under which the simple series dynamo can be conveniently employed are somewhat limited. For general work, and especially in cases where a constant potential difference and not a constant current is required to be maintained, some better method of 'regulation' is essential—that is, some arrangement by which the machine shall be made to develop just as much electrical power as the variations in the external circuit demand from it. The first approximation thereto is obtained by a slight alteration in the manner of winding, giving us what is known as the 'Shunt' dynamo.

In the shunt dynamo the field-magnet coils, instead of being joined up in series with the armature and external circuit, are so connected that they form a 'shunt' *to the external circuit*, and receive, therefore, only a part of the current generated in the armature, the proportion depending upon the relative resistances of the external circuit and the shunt coils. Fig. 161 shows the manner in which the connections are made, and the principle, which is very simple, should be readily grasped. The armature is rotated between the pole-pieces, and a certain E.M.F. is developed in the usual manner. The whole of the current generated passes, as a matter of course, through the armature, and we will suppose that its direction in both halves of the armature is upwards, or from the lower to the upper brush. At the upper brush, B_1, the circuit is divided, two paths being open to the current; one round the coils of the field-magnets, by taking which it augments and maintains the field; and the other through the external circuit, where it can be used to run lamps, or perform such other work as may be required. Both of these paths, however, terminate at the lower brush, B_2, and the quantity of the current which goes round either path is, as we have just indicated, simply inversely proportional to the resistance of that path. In case any difficulty should be experienced in understanding the connections or in tracing the path of the current in the various branches, the arrangement is shown even more clearly in fig. 162, R being the external circuit, S the field-magnet coil, B_1, B_2 the brushes, and D the commutator of the dynamo.

The method of measurement applied to the series dynamo can also be adopted with the shunt machine, for the amount of power absorbed in the armature, field-magnet coils, and external circuit respectively, can be found by multiplying the current in that particular part of the circuit by the potential difference at its extremities. The armature resistance must be very low, otherwise, as it carries the whole of the current, the power absorbed therein becomes considerable ; on the other hand, the resistance of the field-magnet coils requires to be relatively high.

In an actual machine giving excellent results, the resistance ot the armature is a trifle less than one-hundredth of an ohm, while the magnet coils offer 16·93ω, or about 1,700 times as great a resistance. Supposing this machine were driven at such a speed as to develop a potential difference at the brushes of 100 volts, the external resistance R (consisting of a number of lamps in parallel) being half an ohm, then the current in the external circuit would be 200 amperes, and the power usefully employed therein 100 × 200 = 20,000 watts.

FIG. 162.



The resistance of the shunt coils being 16·93ω, and the potential difference at the extremities 100 volts, the current produced therein will be almost 6 amperes. So that 6 × 100 = 600 watts will be absorbed in maintaining the field. The current in the armature of a shunt dynamo is the sum of the two currents in the external branches—viz. the field-magnet coils, and the external circuit, and in this particular case it is 6 + 200 = 206 amperes. The armature resistance is 0·01ω, and since the fall of potential along it is equal to the product of current strength and resistance, the fall of potential along the armature from brush to brush is 206 × 0·01 = 2·06 volts. Therefore the power absorbed in it is 2·06 × 206 = 424·36 watts, which result, of course, might also be obtained by multiplying together the square of the current passing through the armature, and the resistance. Now the whole electrical power developed is

21,024 watts, of which number 1,024 are absorbed in maintaining the field and in overcoming the armature resistance, the remaining 20,000 being usefully expended in the external circuit.

The ratio of the power usefully available to the total power developed, is commonly known as the 'electrical efficiency' of the dynamo, and in the case just considered this ratio is $\frac{20,000}{21,024}$, or the electrical efficiency is slightly over 95 per cent. It is hardly necessary to point out that a very slight increase of the armature resistance would considerably lower this figure, because the armature carries such a heavy current. The electrical efficiency would, on the contrary, be slightly increased if more turns of wire were wound on the field-magnet, because the added resistance would diminish the current strength, although the magneto-motive force would remain unaltered, since the increase in the number of turns would just balance the reduction of the current. Similarly, the field would be practically unaltered if, say, half the number of convolutions were removed from the field-magnet coil, because, the wire being of uniform resistance throughout, the removal of half of it would halve the resistance of, and double the current strength in, the field-magnet coil, supposing the potential difference of 100 volts to be maintained in both cases. The efficiency would, however, be lowered by such a procedure, because twice as much energy would be wasted in heating the field-magnet coils, the energy so wasted being proportionate to C^2R.

Ignoring for the moment the small amount of residual magnetism, it will be observed that in a series dynamo the field-magnets become demagnetised immediately the external circuit is broken, because the whole of the current is then stopped. In the case of a shunt dynamo, however, if the external circuit R in fig. 162 is broken, there is an alternative path left for the current generated by the armature, viz. round the field-magnet coil S. Although under these circumstances the current passing through the armature is less than when the external circuit is completed, yet, since the whole of it passes through the field-magnet coil, the strength of the field due to the field-magnet is always at its maximum when the external circuit is disconnected; exactly opposite to the case of a series dynamo. In the latter machine the most powerful

current is generated and the field is strongest when the terminals are joined by a piece of thick wire; but this proceeding would have the reverse effect upon a shunt machine, because practically no current would flow round the coils on account of the very low resistance of the alternate path.

Although the shunt dynamo (especially if the resistance of its armature is low) is through a certain range less affected by changes in the external circuit than the series dynamo, neither of them is, for many purposes, sufficiently 'self-regulating,' or able to accommodate itself to these external variations. We may require a dynamo to do one of two things: either (*a*) to regulate itself so as to send a *constant current*, or a current of uniform strength, through the external circuit, although the resistance may be considerably varied; or (*b*) we may require it to maintain a *constant potential difference* at the extremities of the external circuit—that is, at the dynamo terminals—under like variations of resistance. No one machine can be constructed to fulfil both these requirements, and we will now consider the best of the many methods of maintaining a constant potential. This consists in the combination, in one machine, of the series and the shunt methods of winding. The simplest way, perhaps, of viewing the arrangement, is to consider the machine as a shunt-wound one, having added to it, round the magnet-limbs, a few turns of wire in series with the external circuit. Then, when the external resistance is made very low, and, as a consequence, the conditions are set up for the current in the shunt coils to be reduced almost to nothing, the magnetic effect of the series coils becomes a maximum, on account of the increase in the strength of the current which flows through those coils, so that the opposite variations in these two sets of coils tend to keep the field more or less constant. It is clear that the success attending this combination will depend largely upon the proper proportions being given to the shunt and series coils, and in order to ascertain what these proportions are or should be for any particular case, we will now introduce a convenient method by which the variation of the E.M.F. developed by a dynamo under varying conditions can be studied.

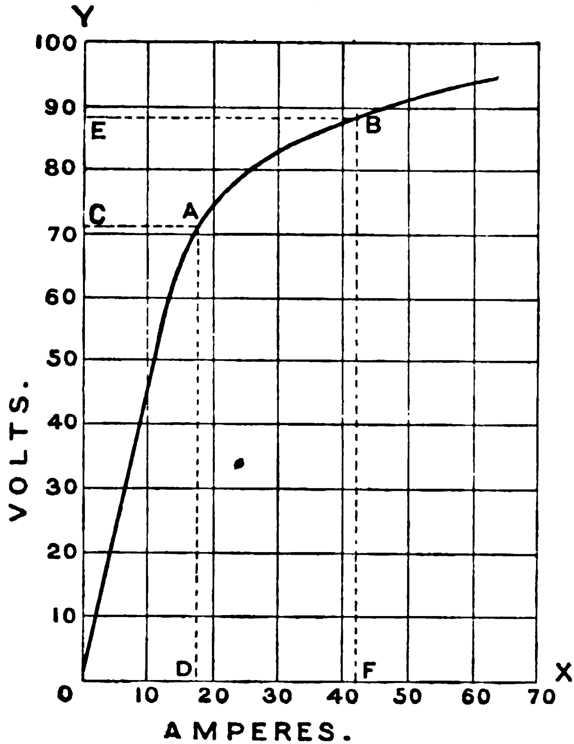
Let us start with the case of a series machine, driven throughout the experiments at a constant speed, and joined up to a set of

suitable known resistances which can be varied as desired. The resulting current can be measured by any suitable ammeter, and, the resistance of the machine and of the external circuit being known, the whole of the E.M.F. developed can be calculated as the product of amperes and ohms. We thus obtain the amperes of current flowing and the whole of the volts of E.M.F. developed, and these two quantities may be similarly found for any number of values which we choose to give the external resistance.

For instance, we might start with the external resistance very high and reduce it by suitable gradations until it becomes as low as safety to the machine will allow. A table might then be made showing the number of amperes flowing at every stage and the volts corresponding thereto. But by means of the 'squared paper' previously referred to, the whole of the experiments can be shown graphically in the form of a curve, known as the 'characteristic curve' of the particular machine experimented with. Fig. 163 represents such a curve, taken from a series machine, driven at a constant speed. The volts calculated are measured off in vertical distances or ordinates, and the amperes in horizontal distances or abscissæ, the intersection of *corresponding* ordinates and abscissæ being points on the curve. The length of the side of a square in the figure represents 10 volts or 10 amperes, but in practice it is better to use a larger sheet of paper divided into a greater number of squares, one side of each square representing 1 volt, or 1 ampere as the case may be. One of the experiments with this machine showed that 70·6 volts were developed when 18·2 amperes were flowing, and the point A on the curve is the result of this particular experiment. It is the point of intersection of the two straight lines, C A and D A, drawn at right angles to O Y and O X respectively, C A being 18·2 units and D A 70·6 units, in length (the unit being one-tenth of a side of one of the squares). Another experiment, which determined the position of the point B, showed that 42 amperes were flowing when 87·4 volts were developed; therefore the distance E B is made equal to 42 units, and F B to 87·4 units. Other points were fixed by similar experiments, and by joining these points together the curve was obtained. Considerable care must be exercised in performing the necessary experiments to

determine one of these curves, and in the region of any decided change in the curvature the number of experiments must be greater than they need be in the more uniform portions of the line. Notwithstanding, however, the exercise of the greatest possible care, some of the points are usually placed a little out of

FIG. 163.



position, owing to experimental error. But experience and theory teach us that zigzag deviations never appear in the curves of dynamo machines, so that when the points do not lie exactly on a regular curve, we can, to a certain extent, correct experimental errors, by striking what may be called an average, with the aid of a flexible ruler.

Were the amperes and volts to increase in the same proportion throughout, the 'curve' would be a straight line; but with every self-exciting series dynamo we get a curve somewhat similar to the one here given—that is to say, with the first part ascending rapidly, then a decided bend, followed by a fairly straight portion making a smaller angle with the horizontal. It has already been pointed out that although the E.M.F. rises as the current flowing round the field-magnets (and, therefore, as the strength of the field) increases, a stage is reached when a given increase in the current does not give a proportionate increase in the field. This happens when the iron in the field-magnets becomes saturated, and it is at this stage that the decided bend in the characteristic curve shows that the amperes are increasing faster than the volts. The student will probably notice the general likeness between this curve and those given in Chapter VII. for the magnetization of soft iron. In fact the experiments here referred to, constitute a very rough method of constructing the magnetization curve for the iron of the field-magnet core, because the magnetizing force is proportional to the current strength, and the magnetic induction varies approximately as the strength of the field projected through the armature, of which strength the value of the E.M.F. is a more or less accurate measure.

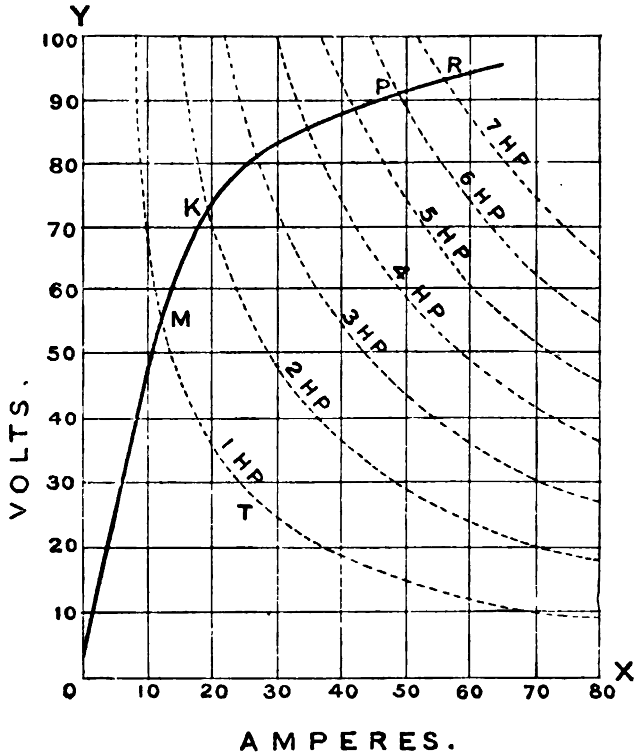
It sometimes happens that by merely glancing at a curve we can criticise the design of a machine in some important respects; for instance, the effect of having too little iron in a machine would be to make the bend occur earlier than it really should do. Other points of criticism will manifest themselves presently.

Reverting to fig. 163, it will be seen that the curve commences, not exactly at the point O, but at a point a little way up the vertical line, thus apparently indicating the existence of a small E.M.F. before the current commences to flow. This actually is the case, and results from the existence, in the field-magnets, of residual magnetism, which provides a weak field and produces a small potential difference at the terminals before the circuit is completed.

The two quantities—current and E.M.F.—plotted in this curve, are those which, when multiplied together, enable us to estimate the amount of power being developed in the whole circuit, for the product of one volt and one ampere is one watt, which is the elec-

trical unit of power, or rate of expenditure of energy, and 746 watts correspond to one horse-power. It follows that we can select any point on the curve and readily calculate what power was being developed in the circuit at the particular moment that that point was determined; for instance, during the experiment

FIG. 164.



which determined the position of the point A, the power developed was $70{\cdot}6 \times 18{\cdot}2 = 1{,}285$ watts.

Such calculations can, in a measure, be avoided by the addition of another set of curves cutting the characteristic at points which correspond to a certain horse-power or fraction of a horse-power. Fig. 164 is a copy of fig. 163, with a number of these

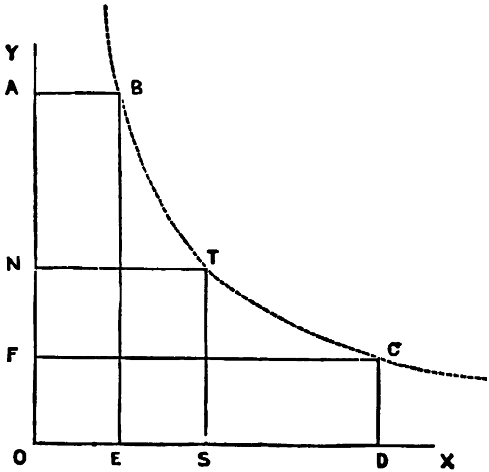
horse-power curves added in dotted lines. At the point M, where the characteristic cuts the 1 horse-power line, the product of volts and amperes is equal to 746 watts, while at K it is equal to $2 \times 746 = 1{,}492$ watts. These curves are also of service in readily showing the manner in which the power developed by a machine varies, when the speed, E.M.F. and current are all subject to change. For example, if the dynamo with which the characteristic curve under notice was obtained were driven at a higher speed, the E.M.F. for a given current would be greater—that is, the vertical distances will be relatively greater than the horizontal ones as the speed is increased, and a curve somewhat similar in shape, but placed above the existing one, will be obtained. Several curves obtained with different speeds may thus be plotted on the same sheet of paper, and the power developed at different stages in each case readily compared, by reference to the horse-power lines.

These horse-power lines may be constructed by a simple, although somewhat tedious, process. As an example let us take the I.H.P. line in fig. 164; T, the nearest point to O, will be equally distant from O X and O Y—that is to say, the perpendiculars drawn from T to O X and O Y will be equal. These perpendiculars are shown in fig. 165, where $TS = TN$, and their product $TS \times TN$ must be equal to 746 units, since T is a point on the curve. Now N T S O is a square, all the sides are equal, and therefore $TS \times TN = TN^2 = ON^2 = 746$, or $ON = \sqrt{746}$. (The unit in fig. 164 is one-tenth of the side of a square, and in every case the unit is that length taken to represent one volt or one ampere.) If, therefore, we take O N and O S equal to $\sqrt{746}$—that is, 27·3 units in length—and draw perpendiculars from N and S, their intersection in T will give the first point on the curve. Then, if any convenient number of rectangles, equal in area to the square, be constructed, the product of two adjacent sides will equal $ON \times TN = 746$. For instance, the rectangles O B and O C are equal to the square O T (O A and O D being each twice the length of O N, and O F and O E being half that length). Therefore, since $AB \times BE$ and $CD \times CF$ are each equal to 746, B and C are points on the curve. This method illustrates the principle in a simple manner, and quicker methods of finding pairs of lines whose products are equal will suggest themselves (Euclid, III. 36). The side of the

square determining the first point on the 2 H.P. line will be equal to $\sqrt{(2 \times 746)} = \sqrt{1492}$, consequently the other points can be found in the same way as before.

It will be remembered that the characteristic in fig. 163 was constructed by measuring the amperes, and calculating the total volts ; but it is less troublesome to join up a voltmeter and measure directly the volts *at the terminals* of the dynamo, and then plot a curve showing the potential difference at the terminals (instead of the total E.M.F.), corresponding to various values of the

FIG. 165.

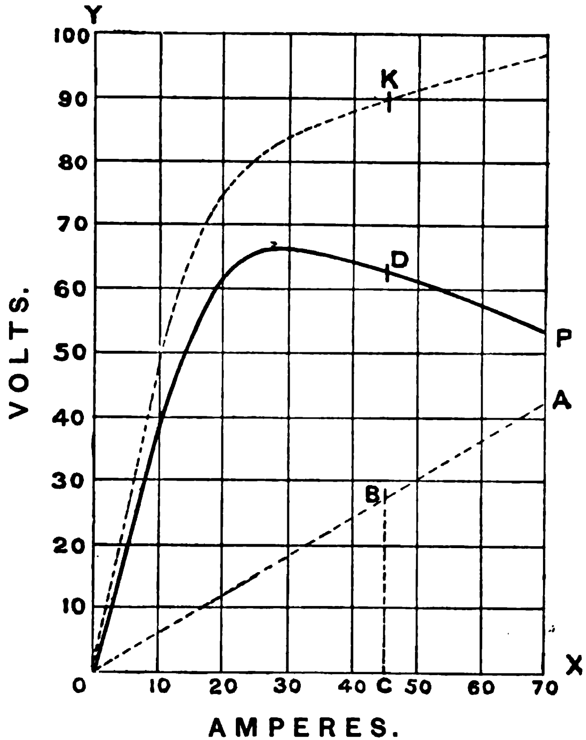


current. In fact, this latter curve, usually called the external characteristic curve, is the more useful of the two, for in practice it is the external potential difference which concerns us most.

In fig. 166 the curve O P is the *external* characteristic, obtained from the same machine as the previous curve, running at the same speed. The bend is now even more clearly defined ; in fact, after a certain point the potential difference falls as the current is increased. One reason for this bending down is, as we have said, the magnetic saturation of the iron, and it is also partly caused by the heavy current in the armature distorting the field.

The curve shows us then, at a glance, the particular current strength at which we can get the maximum external potential difference at a given speed, and of course, by inserting the horse-power lines, we can also see the amount of power absorbed in the external circuit. Now the remainder of the E.M.F. is absorbed in

FIG. 166.



overcoming the resistance of the armature, and since this armature resistance is constant, this portion of the E.M.F. (found by multiplying the armature resistance and the current) will always be proportional to the current flowing. In fact, if we plot the 'curve' for current and E.M.F. expended in the armature, we get the straight line O A. And, further, if at any point, say C, we add

together the vertical distance from the base line to the line O A, and the vertical distance to the external characteristic—that is to say, if we add C B and C D—we get a line proportional to the whole E.M.F., giving the point K on the original total characteristic. In this manner we can construct the total characteristic curve, now shown as a dotted line; or, given this curve, we might draw the line O A, and, by subtracting, deduce the external characteristic.

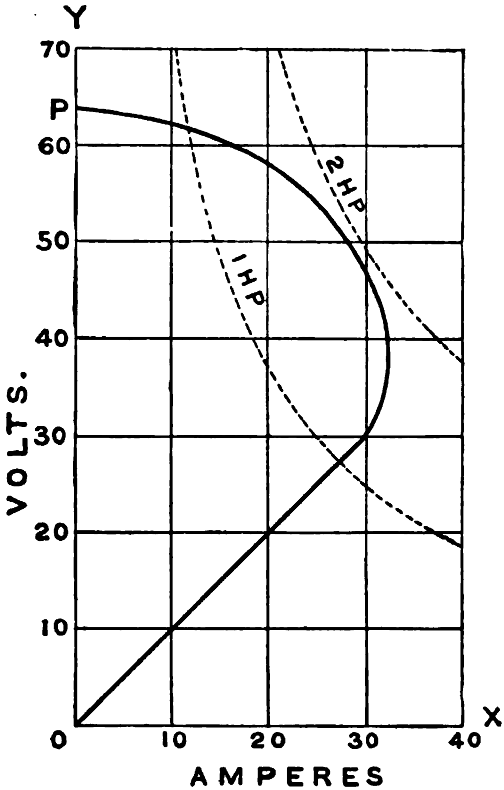
The greater the armature resistance the greater will be the fall of potential along it for any given current strength, and therefore also the greater will be the angle which O A makes with the horizontal. In fact, the tangent of this angle is proportional to the armature resistance, for $R = \frac{E}{C} = \frac{BC}{OC} = \tan BOC$.

If this angle happened to be 45°, we should know that the armature resistance is 1 ohm, for the tangent of 45° is 1. In the present case the angle is 31°, the tangent of which is 0·601; therefore, the armature resistance is 0·601 ohm.

The 'external' characteristic for a shunt-wound dynamo is very different, as will be seen on referring to fig. 167, which is the curve obtained from such a machine, the vertical distances being proportional to the potential difference at the terminals, and the horizontal distances to the current in the external circuit. As before, the scale taken is such that a side of a square represents 10 volts or 10 amperes. If we suppose the series of measurements to be commenced when the external circuit is disconnected and its resistance therefore infinite, the potential difference at the terminals of the machine will then have its maximum value, and we shall obtain P, the highest point on the curve. With this particular machine running at a certain constant speed, the maximum potential difference happened to be 63·5 volts, and as, of course, no current could flow in the external circuit, the point P is placed on the line O Y, at a distance of 63·5 units above O X. When very high resistance is introduced, so as to allow just a feeble current to flow in the external circuit, the potential difference at the terminals falls slightly, and continues to fall as the resistance is reduced and the current consequently increased. At first the amount of current abstracted from the field-magnet coil makes

but little difference to the strength of the field, and therefore the potential difference falls but slightly. But when the external resistance is so low that the current becomes about 20 amperes, the amount abstracted from the shunt begins to have a very

FIG. 167.



decided effect upon the strength of the field. The potential difference at the terminals or brushes then falls considerably, and, the current remaining fairly constant during a small range, the effect is seen in the curve as a sudden bend downwards—almost, in fact, a perpendicular line. The resistance being still further

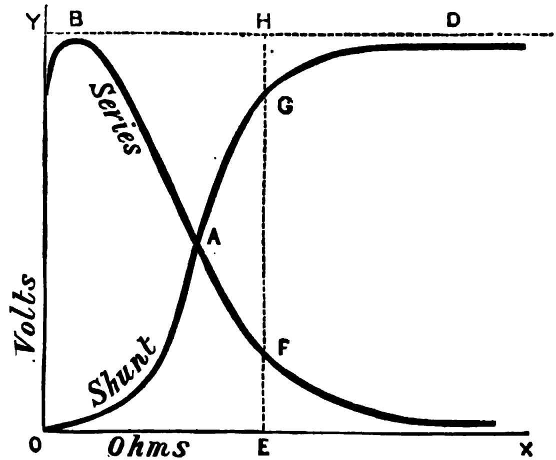
reduced, not only does the potential difference fall, but also the current, giving the curve a turn *backwards*, until presently the field-magnets lose their magnetism, and when the terminals are short-circuited the curve terminates in the point O, potential difference and current being then reduced to *nil*. As the field-magnets, however, rarely lose the whole of their magnetism, a feeble current usually continues to flow after the terminals have been short-circuited, so that the curve may really end at a point some little distance from O along the line O X.

In most modern machines the armature resistance is much lower than that of the machine from which the curve given in fig. 167 was obtained, and, consequently, in such machines the curve remains approximately horizontal for a proportionally greater distance from the point P, indicating that a much larger current can be taken from the armature without materially lowering the potential difference between the brushes.

Although these characteristics give us a clear idea of the manner in which the external potential varies with a variation in the current strength, we can better understand the method of combining—or, technically speaking, 'compounding'—the series and shunt windings to obtain self-regulation, by constructing and comparing other curves, which show how the external potential difference and the external resistance vary together, both in a series and a shunt machine. As before, the ordinates (fig. 168) represent volts, but the abscissæ now represent ohms. The figure shows two curves, one for a shunt and the other for a series machine, both starting at or near the line O Y, when the external resistance is very low. In the case of the shunt machine, the curve shows the potential difference to be very low at first, gradually rising for a short distance as the external resistance is increased, until at a certain stage it ascends suddenly, this, as we know, occurring when the external resistance is high enough to allow the field-magnets to become strongly magnetised. On the other hand, the curve from the series machine is at its highest point B, when the resistance is low, and it falls almost in the same manner as the other curve rises. This curve can hardly start on the line O Y, because, of course, when the resistance between the terminals is *nil* no difference of potential can exist, but it quickly

reaches the highest point as the resistance is increased, and then rapidly falls as the further increase of resistance reduces the current sufficiently to considerably weaken the field. Now, if in one machine it is possible to so proportion the shunt and series windings that the maximum effect of the series coil is equal to the maximum effect of the shunt coil, and also that the effect of the series coil diminishes in the same proportion as the effect of the shunt coil increases, these two windings will counterbalance each other through a considerable variation of external resistance, and

FIG. 168.



the result will be a constant external potential difference. The first condition would make the height of the highest points on each curve equal; while if the second condition were attained, the slope downward of the one curve would exactly correspond to the slope upward of the other. And at any point, such as E, the potential difference due to the series coil added to that due to the shunt coil—that is, E F + E G—should give us the vertical line E H equal to the height of the highest point on each curve. Likewise, the point of intersection A should be midway between B D and O X, and the heights of the two curves added together throughout

should produce the straight line B D. Then the potential difference at the terminals being constant, the current will vary regularly with the resistance, and we shall consequently obtain a straight line for the characteristic curve of the compound-wound machine. It is evident that if the series coil acts too powerfully the effect will be to raise the point B—that is, to make the potential difference at the brushes higher when the external resistance is low and the current strong, than when the external resistance is higher, and *vice versâ*.

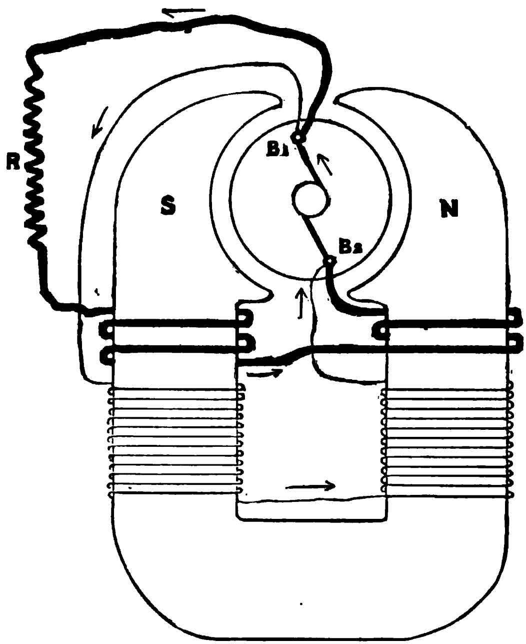
Since, however, the effect of an alteration of the speed of rotation of the armature is so different in the case of a series as compared with a shunt machine, a dynamo compounded in the manner just described is only self-regulating at approximately the speed for which it was designed; for at any other speed the two windings do not compensate each other.

In the case of a series machine, if, for instance, the speed were doubled and the external resistance increased sufficiently to keep the current the same, the strength of field would remain unaltered and the E.M.F. would be increased almost, but not quite, twofold by the doubled speed. On the other hand, if, with a shunt dynamo, by increasing the external resistance we maintain the external current constant when the speed is doubled, the current in the shunt coil, and therefore the strength of the field, increases instead of remaining the same, as does that of a series dynamo. While, if at the doubled speed the resistance were reduced to make the current in the shunt coil the same as at the lower speed, the external current would be greatly increased in strength. Therefore, because of these different effects of an alteration of speed on the series and shunt windings, the dynamo will only regulate perfectly when driven at or near the particular speed for which it was compounded. In practice the speed at which the machine is to run is usually determined beforehand, then at this speed the shunt coils alone must be able to provide a sufficiently strong field to develop at the terminals the required potential difference when the external circuit is disconnected, while when the external resistance is made as low as it ever will be in actual working, the ampere-turns in series should, with the assistance of the shunt coil, be able to maintain this same field.

The connections of a compound-wound dynamo, and the paths taken by the current through its coils, are typically illustrated in fig. 169.

As in previous similar figures, B_1 B_2 are the brushes. At B_1 the current generated in the armature divides, part going through the shunt coils wound on the lower parts of the limbs of the field-

FIG. 169.



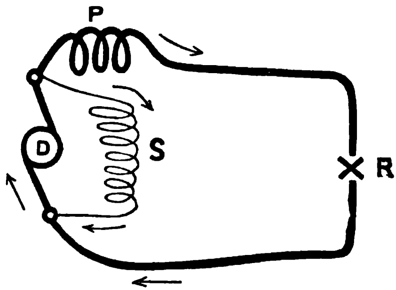
magnet and thence returning to the brush, B_2; the remainder passes through the external circuit R, then round the series coils on the upper part of the field-magnet, and thence to the brush, B_2. The shunt coils are wound with comparatively fine wire, but, of course, the resistance of the series coils must be kept very low as they carry the main current, and they are composed, therefore, of a few turns of very thick wire. The relative positions of the two

sets of coils is not always that shown, the series coil being sometimes wound outside and sometimes inside the shunt coil; but this not very important point is decided by convenience in construction rather than by theory.

To render the path of the current even more easily understood, fig. 170 is added; R is the external circuit, D the armature, S the shunt coil, and P the series coil.

In some cases a machine is designed to produce the result referred to on p. 345—that is, to make the potential difference at the brushes higher when the external resistance is low and the current strong, than when the external resistance is comparatively great and the current feeble. Let it be supposed, for example, that a large and varying number of lamps joined in parallel have to be supplied from a dynamo at a considerable distance away, in which case the resistance of the main leads would be comparatively high, say, one-tenth of an ohm. If the maximum current were 100 amperes, the fall of potential between the machine and the lamps would be $100 \times \cdot 1 = 10$ volts; but when only one-tenth of the lamps are in use the current would be 10 amperes, and the fall potential in the mains only $10 \times \cdot 1 = 1$ volt. From this it is clear that if the lamps required a potential difference of 100 volts, a machine which could simply maintain a potential difference of 100 volts between its brushes would be unsuitable. But if its series coils were made to preponderate over the shunt coils in the manner indicated, and to such an extent that 110 volts were developed with a current of 100 amperes in the main circuit, the loss on the mains would be compensated for and the requisite potential difference at the lamps would be maintained. A machine so constructed is said to be 'over-compounded.'

FIG. 170.



As a matter of fact, were a machine to be designed so that

the maximum effect of the series coil alone were fully equal to that of the shunt coil, as indicated in fig. 168, the machine would be over-compounded, because when the current in the external circuit arrives at that strength at which the pressure at the brushes of a simple shunt machine would commence to drop, that same current passing through the series coils maintains the field, and, consequently, also the pressure between the mains, the only reduction in the pressure between the ends of the shunt coil being that due to the fall of potential along the series coil, which, although thick, offers of course an appreciable resistance.

The over-compounding of a machine is also of service in compensating for the slowing down of its driving-engine or the slipping of the driving-belt if one is employed, both of which effects are usually appreciably greater as the current taken from the dynamo increases.

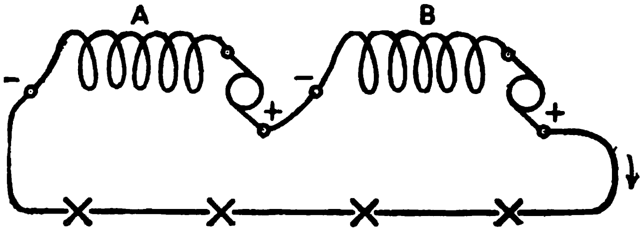
The combination of shunt and series coils for the field-magnet as described, is the method commonly adopted to obtain a constant external potential, notwithstanding variations in the external circuit. We shall not refer to any other methods, many of which are only theoretically possible, but may briefly mention some interesting experiments of the Drs. Hopkinson which bear somewhat upon this point. They disconnected the field-magnet coils of a certain machine, and, having placed the brushes in the position for an undistorted field, connected them to the terminals of a Siemens dynamometer. Then, when the armature was driven at 1,380 revolutions per minute, the current, due solely to residual magnetism, was 52 amperes; but on giving the brushes a slight forward lead, the current fell almost to zero, because the field due to the current in the armature was then opposing that maintained by the residual magnetism. But when a backward lead was given to the brushes, the polarity of the armature was shifted round so as to enhance the residual magnetism in the pole-pieces; the armature, in fact, now generated its own field, and a current of 234 amperes was obtained. Since the field in such a case is almost proportional to the current flowing in the armature, which increases as the external resistance falls, such an arrangement would regulate for constant potential; but it is not practicable owing to the destructive sparking which arises in

consequence of the coils being short-circuited by the brushes while fairly active.

It should always be borne in mind, however, that the range over which a simple shunt-wound machine is self-regulating becomes increased as the armature resistance is diminished; and as in many modern machines, more particularly large ones, such as those employed for Central Station work, the armature resistance is exceedingly low, compound winding is not resorted to so often as might otherwise be expected.

We have seen that it is possible and frequently necessary to connect primary cells, sometimes in series and sometimes in parallel; the former device being adopted when an increase in electro-motive force is desired, and the latter when it is sought to

FIG. 171.



obtain an increased current strength due to the reduced internal resistance. In just the same way it is sometimes necessary to join two or more dynamos, either in series or in parallel, to feed the same circuit. Connection in series is usually adopted on a constant current circuit, such as an arc light circuit where all the lamps are joined in series, and a current of, say, 10 amperes is required through each. Series-wound machines, of a special type to be presently described, are employed for such a purpose, and little difficulty need be experienced in throwing a second machine in circuit while the first is running, without interfering with the lamps. For example, in fig. 171, suppose the machine B to be working at nearly its full capacity, and that more lamps are wanted in circuit; it therefore becomes necessary to throw the second machine A in series with B to provide the required

increase in electro-motive force. Now, if the machine A which is at rest be joined up as shown in the figure, but with its field-magnet coils short-circuited, the whole of the current will pass through the short-circuiting connection and through the armature, the field not becoming excited, so that the machine cannot start as a motor. The armature which is then carrying the full current of, say, 10 amperes can then be driven up to its proper speed, when the field-magnet can be thrown in circuit, so that this machine can begin to assist the other. The automatic regulators of each machine should divide the work between the two, keeping the potential difference between the terminals of one machine approximately equal to that between the terminals of the other. Better regulation is however, obtained by so arranging matters that the field-magnet coils of the two machines are joined directly in series, and the regulating shunt connected across the two, one regulator only being employed.

It is clear that, if necessary, the machine B could be removed from the circuit in the same manner, by first short-circuiting its field-magnet coils, and then letting it run down, and indeed this arrangement is usually adopted when, for example, a machine shows signs of distress after a long run and requires overhauling. The second machine is first inserted in circuit, and automatically takes an increasing proportion of the work as the first one is slowed down and finally short-circuited. Appropriate switching arrangements are, of course, essential for making these changes, as the electro-motive force usually amounts to one or two thousand volts.

It is needless to mention that if the second dynamo were incorrectly joined in circuit, its field-magnet would be magnetised in the reverse direction, and the armature would, when rotated, generate an electro-motive force opposing that of the machine already in circuit.

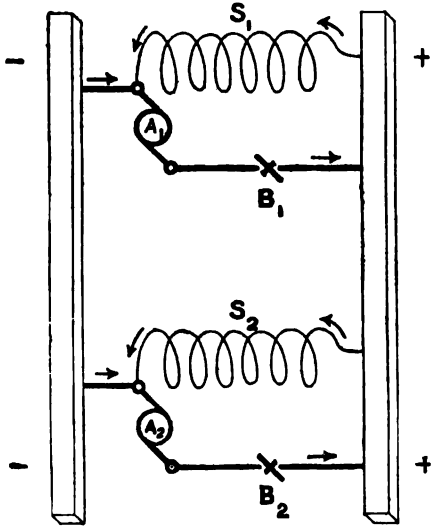
When lamps are joined in parallel circuit between two mains, an increase in the number placed in circuit means a reduction in the resistance between the mains, and a corresponding increase in the strength of the current which the dynamo is called upon to supply, it being imperative that the potential difference between the mains shall remain unaltered, notwithstanding considerable changes in the

current strength. In such a case any dynamo employed to assist one already at work must be joined in parallel with it, and simple shunt machines lend themselves most readily to such working. A shunt machine while at rest cannot, however, be switched on to the circuit in parallel with a machine already working and maintaining a pressure of, say, 100 volts between the mains, because of the enormous current which would flow through the stationary armature. There are two paths open for such a current between the terminals of a shunt-wound machine, one through the field-magnet coils and the other through the armature. The armature resistance should be extremely low; if it were one hundredth of an ohm the current through it would be no less than $\frac{100}{\cdot 01} = 10{,}000$ amperes, supposing the armature to remain at rest and the pressure of 100 volts to be maintained. Such a current would, if maintained, burn up the armature, and although, for reasons which will be subsequently explained, it would probably not continue for any length of time, it is clear that the risk of its even starting must be avoided. Consequently, it is necessary to drive the second machine up to its normal speed, and wait until its field-magnets are fully excited and the pressure of 100 volts is developed between its terminals before switching it into circuit. An even better plan is to arrange the connections in such a way that the field-magnet coils may be joined to the main or 'omnibus' leads independently of the armature.

Then, in order to bring a second machine into play, its field-magnet coils are first joined across between the mains, when the potential difference of 100 volts starts and maintains through the coils the requisite current to fully excite the field-magnets. The armature should then be driven up to its normal speed, and when, as shown by a voltmeter connected across the brushes, it is developing 100 volts, it can be switched in circuit, and the admission of steam to the engine cylinder increased, either automatically or by hand, until the machine supplies its share of current to the main circuit. In fig. 172, two dynamos are shown supplying a common pair of mains, and of course any number of machines may be so connected. It will be noticed that in each case one brush and one end of the field-magnet coils are joined

to the negative main by a common lead, in which a switch may be inserted, while another switch may be placed between the other brush and the positive main. A third switch may be inserted between the positive main and the field-magnet coils. In throwing a machine out of circuit the admission of steam should be reduced until the current passing from the armature falls to a small amount, when the armature switch can be opened without any appreciable spark passing. The field-magnet coil should then be disconnected, but if this were done without any precaution being adopted to prevent it, a considerable spark

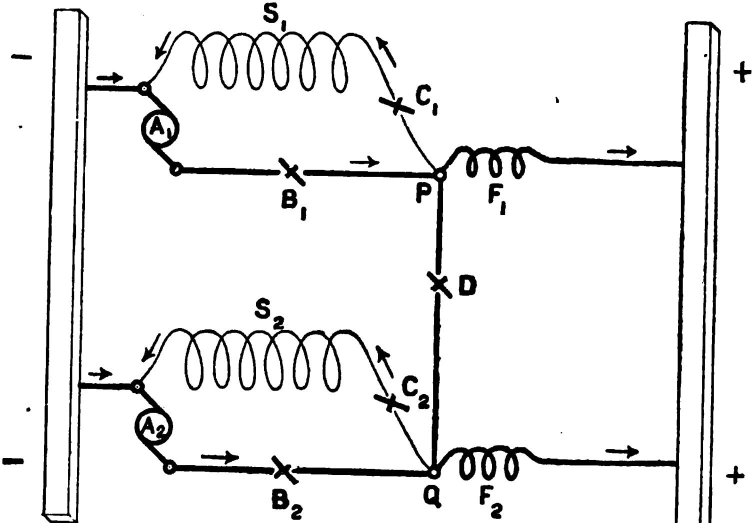
FIG. 172.



would occur at the switch contact point, on account of the high self-induction of the field-magnet. It is therefore advisable to first shunt the field-magnet coils by a non-inductive resistance of approximately the same value, and then, when the circuit with the positive main is broken, the extra current will circulate in this shunt and die away, thus preventing any appreciable spark at the contacts of the switch.

In the St. James and Pall Mall installation a number of shunt-wound machines are worked in parallel, and an automatic switch is placed between each armature and one of the mains, as shown at B in fig. 172. This switch consists of a lever carrying a soft iron armature or keeper, and an inverted U-shaped copper connecting piece, both on the same side of the point at which the lever is pivoted. When this end of the lever is depressed the legs of the ∩ each dip into a mercury cup and thus complete

FIG. 173.



the armature circuit, which passes once round two soft iron cores placed under the soft iron keeper. When the machine is being started this connection is made by hand, and directly the current starts the soft iron cores attract the soft iron keeper and hold this end of the lever down, thus maintaining the circuit. Should the current fall below, say, 25 amperes, a weight at the other end of the lever operates and immediately breaks the circuit, so that not only is the armature automatically disconnected at the right moment when the engine is slowed down for the purpose of

throwing a particular machine out of circuit, but a like disconnection also occurs should any accident happen to either the engine or the machine.

Compound machines are also sometimes worked in parallel, but the arrangement is necessarily more complicated, and the liability to accident when making changes greater, than in the case of shunt machines. The method of connecting devised by Mr. W. M. Mordey and illustrated in fig. 173 is probably the best, and is certainly satisfactory when the machines are similar. Two machines are shown in the figure, connected across between the positive and negative main leads, from which the lamp circuits may be tapped off, the object being, of course, to enable the load to be equally divided between the machines. One end of each of the series coils F_1 F_2 is shown connected to the positive main, the other ends being directly joined together by the wire P Q. One end of the shunt coil S_1 is also connected to P, and the corresponding end of the shunt coil S_2 to Q, the other ends being joined to the negative main. The points P and Q are always at the same potential, or, if not, an equalising current will at once flow between them, and the consequence is that the difference of potential between the ends of the two series coils is always practically the same, and the currents passing through them must be equal if their resistances are equal; and also the potential difference between the ends of the two shunt coils is the same and the currents in them will be equal if their resistances are equal. Therefore the strength of field will be the same for both machines, and they will equally share the work when driven at the same speed.

Should the machines be unequal the matter is not quite so simple, as among other things the resistances of the shunt and series coils of the two machines must be so proportioned that each will get the requisite amount of current to excite the field-magnets up to their proper value.

It is evident that as the object of the wire P Q is to keep the two points P and Q at the same potential, it must be of sufficiently low resistance to prevent any appreciable fall of potential along it, notwithstanding the flow of an equalising current of considerable strength.

B_1, B_2, C_1, C_2 and D represent switches to facilitate the throwing in and out of circuit of either machine. Suppose A_2 is to be brought into play while A_1 is working, C_2 and then D should be closed so that currents flow in the proper direction through S_2 and F_2 to excite the field-magnet coils, and then, the armature being run up to the required speed, its switch B_2 may be closed, and the machine then takes up its proportion of the work.

CHAPTER X.

DIRECT CURRENT DYNAMOS—*continued*

WE will now illustrate and describe some of the best modern direct-current dynamos, directing attention in each case to those details which are likely to prove most instructive in showing how theoretical principles are applied, and how, in practice, mechanical and economical considerations sometimes cause a deviation from forms which a narrow theory might show to be the best.

The student is recommended to pay particular attention to the methods adopted for securing mechanical strength and durability. It may be observed, for example, that it is quite as important to prevent the conductor being stripped from an armature as to efficiently insulate it. Again, while a waste of power, such as is evidenced by the heating of the iron core by eddy currents, is to be deprecated, any waste which shows itself in such a manner as the undue heating of bearings is equally, or even more, to be avoided. In both cases the power applied to the shaft is wasted--in the former case after, and in the latter case before, it has been transformed into electrical power.

Fig. 174 illustrates a dynamo constructed by Messrs. Easton, Anderson & Goolden, the armature being of the Gramme ring type, and the field produced by an inverted horse-shoe magnet. This particular machine is compound-wound, and the arrangement is therefore similar to that depicted in fig. 169. A vertical section of the machine at right angles to the shaft is given in fig. 175. The bed-plate is of cast-iron and includes a solid piece, D, in the centre, directly under the armature and field-magnet, to form the

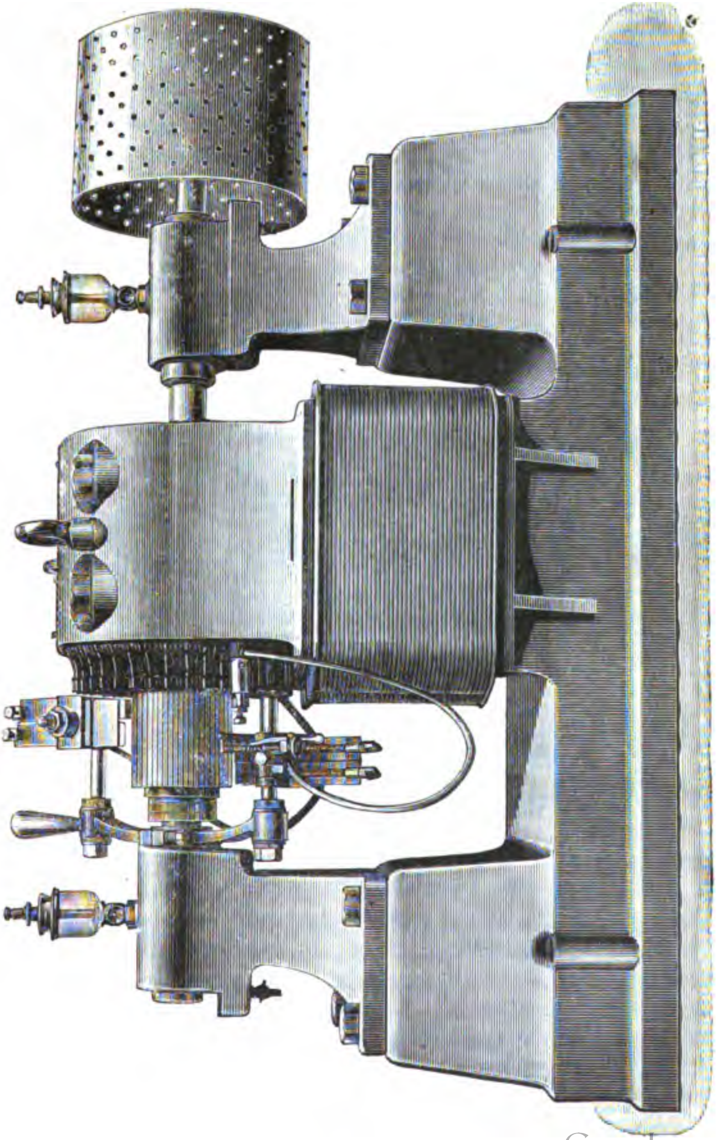
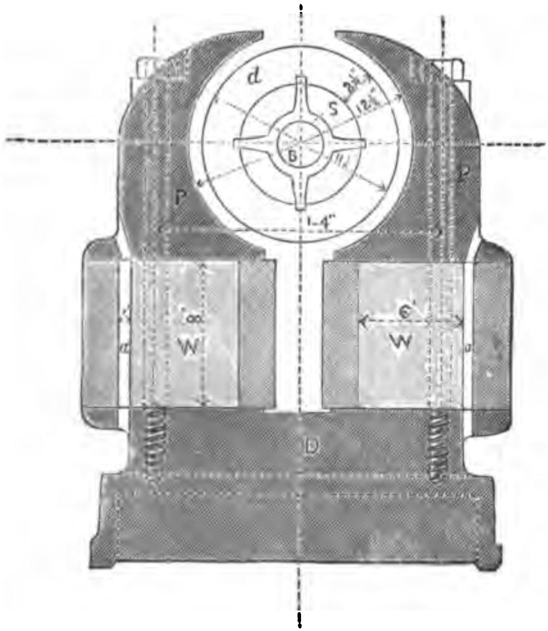


Fig. 174.

yoke of the latter. But wrought-iron is employed for that portion of the cores round which the field-magnet coils are wound, each core, W W, consisting of a slab of soft hammered scrap-iron; thus giving the advantage, previously referred to, of economising copper wire, by obtaining the requisite magnetic conductivity with the minimum sectional area. The pole-pieces, P P, are of grey cast-iron, and the sectional area of all the cast-iron portions is

FIG. 175.

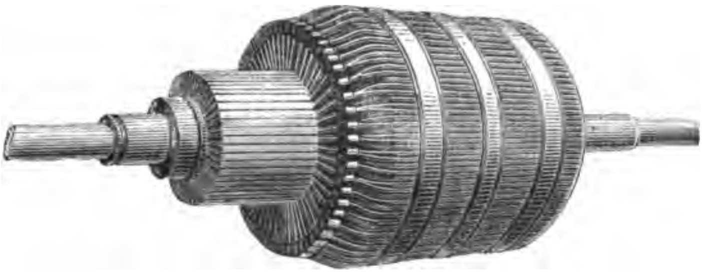


made greater than that of the wrought-iron portions to compensate for the lower permeability as compared with that of the excellent iron forming the core. The cast-iron pole-pieces are here tapered away to the top, but it is found that any considerable reduction of the area of the magnetic circuit in this manner tends to make the field through the armature stronger at the lower part than at the upper, with the result that there may be, especially in large

machines, a considerable downward pull on the armature. In more recent machines, as will be seen, the section of the iron is not reduced more than is absolutely necessary at any point.

Two long bolts pass through each of the pole-pieces and the wrought-iron cores, screwing, at their lower extremities, into the solid portion of the bed-plate which forms the yoke-piece, and thus holding these parts firmly together. The coils are wound so as to leave a space between the wire and the outer face of the wrought-iron core, as shown at *a a* in the figure, forming thereby an effective means of ventilation; for as the wire gets warm its heat is imparted to the air inside this space, and this air rising, a constant circulation is maintained and the heat carried off by a steady draught of cold air.

FIG. 176.



In the particular machine illustrated the series winding consists of twenty-five convolutions of copper strand, composed of nineteen No. 15 wires (standard wire gauge), a stranded conductor being much more flexible and more convenient to wind than a solid one, although it occupies a little more space. Over this is wound the shunt coil, which consists of 2,712 turns, its resistance being 20·6 ohms. In order to afford a means of obtaining this resistance with this particular number of convolutions, two sizes of wire are employed—viz. Nos. 15 and 16, S.W.G.—the respective lengths of these two wires being adjusted to satisfy the conditions.

The complete armature is shown in fig. 176. The core consists of a number of very thin flat rings of well-annealed charcoal iron, as shown at *d* in the sectional view (fig. 175). The outer diameter of each iron ring or disc is 11½ inches, and its inner

diameter 9¼ inches. Four rectangular notches are cut at equal distances round the inner edge of each disc : a sheet of thin paper insulates each disc from its neighbours, the whole of them being held tightly together by two rigid end-plates. Upon the Bessemer steel shaft B is keyed a gun-metal spider S, having four radial arms, its length along the shaft being equal to that of the finished core, and the extremities of the arms fitting accurately into the notches in the discs. The student will remember the necessity for avoiding, as far as possible, the use of iron in the interior of a Gramme ring, and will therefore understand the reason for making the spider of gun-metal. It should also be borne in mind that, although it is absolutely necessary to efficiently insulate the thin plates into which the core is divided, yet, in consequence of the thinness of the discs, the space occupied by the insulation forms a considerable portion of the whole, whence the magnetic resistance is proportionally increased. In this particular case, 80 per cent. of the core consists of iron and the rest of paper.

The armature conductor consists of cotton-covered copper wire of No. 9. standard wire gauge, lying round the core in one layer, and offering a resistance, from brush to brush, of 0·048 ohm. There are two convolutions in each section, the adjacent ends of neighbouring sections being soldered to radial lugs projecting from the commutator bars, as shown in fig. 176. There are seventy-six such sections, and, consequently, seventy-six bars in the commutator, these bars being of hard-drawn copper insulated from each other by mica strips 0·75 mm. in thickness. Mica is almost the only material now used for this purpose, for which it is eminently suitable, because of its excellent insulating properties, its great durability, and its practically perfect cleavage, in consequence of which it can be procured of any desired thinness.

As the length of conductor parallel to the shaft is considerable, there is a risk of its bulging out when rotated at a high speed, a tendency which would be assisted by the drag on the conductors due to the field, and by the rise in temperature and consequent expansion of the wire caused by the current itself. Any such bulging out or stripping of the conductor is prevented by binding the armature with several turns of fine strong wire in three places, as shown in fig. 176.

The speed of the machine is 1,050 revolutions per minute, at which it is capable of giving a current of 75 amperes, with a potential difference at its terminals of 100 volts.

The brushes consist of flat tough copper strips, fixed in adjustable holders, which are carried by the horizontal arms projecting from the rocking lever, as shown in fig. 174. This lever is provided with an insulating handle, by means of which it can be rotated in either direction round the axis of the shaft, thus affording facilities for altering the lead of the brushes to suit the requirements. Each brush can also be fed through its holder while the machine is running by means of a 'feed' screw. The lever is carried on a projection from the standard supporting the bearing, and is made in two pieces bolted together, so that it can be readily tightened up on its bearing, or, if necessary, removed. The horizontal arms are insulated from the lever by hard fibre collars; and, in addition to the feeding screws, spiral springs, with adjusting screws, are provided for varying the pressure of the brushes on the commutator, the pressure being always as light as is consistent with reliable contact.

The brushes are shown lifted from the commutator; and it will be observed that they can be adjusted along the bars, so as to press upon different parts when the machine is running, and thereby distribute the wear.

The shaft-bearings are of phosphor bronze, and the rim of the pulley is perforated with a view to afford a better grip for the belt.

In fig. 177 we illustrate a somewhat larger machine, with a drum armature, constructed by the same firm. This also is compound-wound, and is designed to give a current of 320 amperes with a pressure of 110 volts at the brushes, when driven at a speed of 600 revolutions per minute. It will be observed that the field-magnet cores are built up in a more simple manner than those of the ring armature machine previously illustrated, each of the two cores with its pole-piece consisting of a single slab of wrought iron fixed by two vertical bolts to the cast-iron bed-plate. Each slab is machined out to fit the slot in the bed-plate, and also to form the cylindrical space in which the armature revolves. It will be noticed that the armature is comparatively longer, extending further beyond the pole-pieces than does the ring armature, and this difference is

common to all machines of these two classes. It is due to the fact that diametrically opposite conductors have to be connected

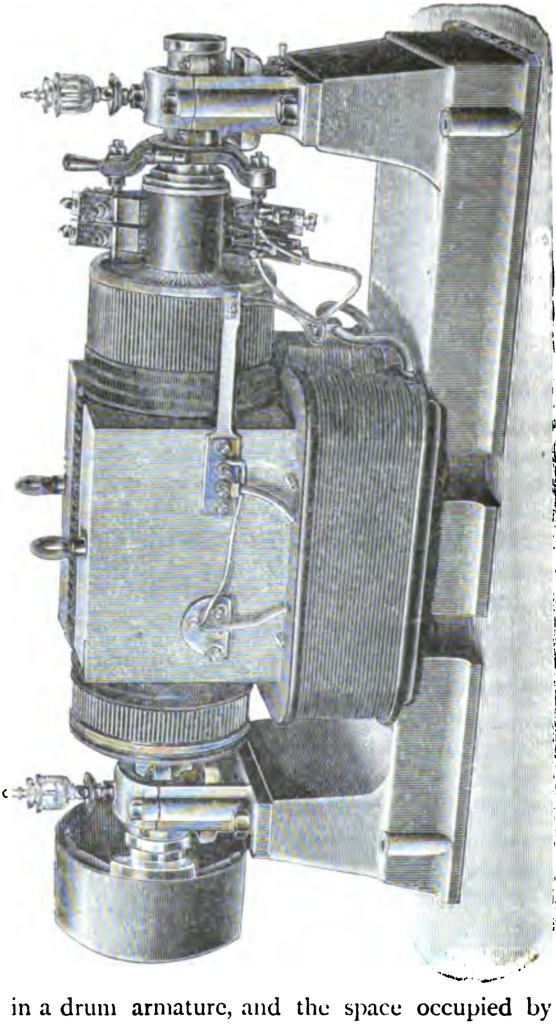
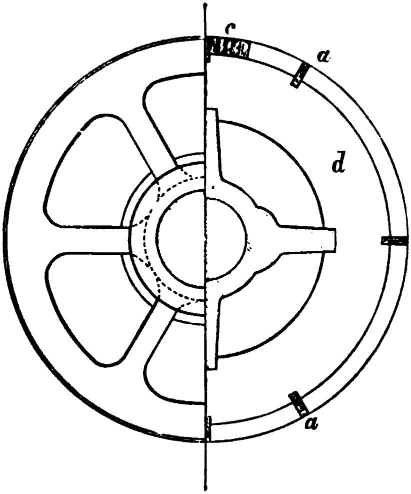


FIG. 177.

together in a drum armature, and the space occupied by these cross connections, no matter how they may be arranged, is considerable.

The core itself extends only through that part of the armature actually embraced by the pole-pieces, so that the active conductors project a considerable distance over the edges of the core, and one important feature in the machine under notice is the manner in which these projecting ends are rigidly held in position. Fig. 178 gives an end view of the armature, at right angles to the shaft, from the end which is remote from the commutator, the right-hand half of the figure showing a section through the middle of the armature, and the left-hand half being a view of the end itself. At this end, as shown on the left-hand side, is a brass ring connected to and driven from its hub by six spokes. The ends of the active conductors fit into the periphery of the ring, being separated from each other by hard wood distance pieces, so that even at the ends these conductors are held rigidly in position. The method of attaining the same result at the commutator end will be considered presently, and it may be mentioned that the securing of the ends of the conductors from vibration while the machine is running is important, because it entirely prevents the occurrence of a common fault in drum armatures, viz. the failure of the electrical connection between the active conductors and the cross connectors, or the connections to the commutator bars.

FIG. 178.



The core is built up of thin discs *d* of soft Swedish iron, every disc being insulated from its neighbour by a sheet of thin paper, and the sectional half of the figure shows the manner in which these discs are driven from the steel shaft. A four-armed gun-metal

spider is keyed to the shaft, and the ends of the arms fit into notches in the inner edges of the core discs as shown. Round the periphery of each disc are eight equidistant notches, and these, when the core is built up, form eight grooves along the entire length of the core. A strip of vulcanised fibre, *a*, also equal in length to the core, is driven tightly into each of these grooves, and these fibre strips form an effective means of driving the armature conductors. The conductors themselves, as shown at *c*, are rectangular in section, and project the same distance from the surface of the core as do the fibre driving strips. They are insulated from each other throughout their length by strips of mica, and from the core by sheets of micanite, the latter consisting of small pieces of mica made up into sheet form by means of shellac while under pressure. The armature is also bound round at a number of places with thin steel wire, which is likewise insulated from the conductors by a layer of mica. The conductors are laminated as described on page 431 to avoid the generation of eddy currents in them.

Fig. 179 shows a side view of half of the armature, including the commutator and one bearing, the upper half being in section. The commutator segments, S, are of hard-drawn copper insulated with mica, and one end of each segment is dovetailed into a brass strip, T, which is connected as shown to the active conductors. These radial brass strips do not touch each other for the greater part of their length, thus allowing space for ventilation between them; but their outer ends are thickened, and with the mica insulation between these ends they form a stiff ring, which rigidly holds the ends of the active conductors and gives the advantages obtained by the use of the brass ring, previously referred to, at the other end of the armature. The lower ends of the brass connecting strips to the right, and the left-hand ends of the commutator segments, are shaped as shown, to fit into grooves in two wrought-iron rings. The grooves are heavily insulated with mica; the right-hand ring bears against a shoulder on a cast-iron sleeve, and when the left-hand ring is forced up tightly in position, by means of a steel nut, the whole of the segments are rigidly fixed. The V-shaped grooves in the clamping rings afford an extremely good means of securing the segments, and this method is undoubtedly preferable to that frequently employed,

in which the rings press only against the upper edges of the segments.

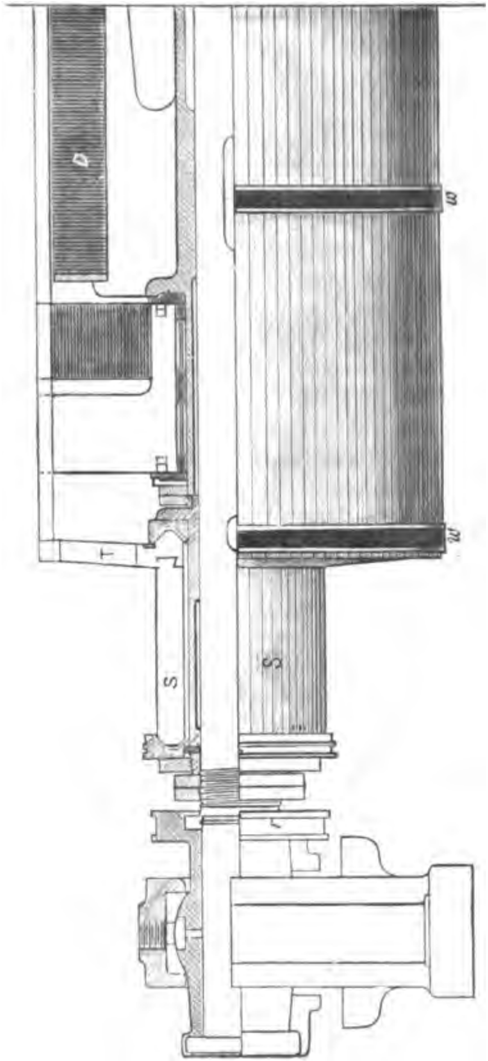


FIG. 179.

The copper strips which form the cross connections can be seen between the brass strip T and the core-plates *d*; space for ventilation is provided between them, their edges fitting into notches in fibre rings, which hold them in position and keep them equally spaced.

Two sets of steel binding wire encircling the armature are shown at *w w* in the figure; the armature is similarly bound at a number of places throughout its entire length.

The bearings in which the armature shaft revolves have spherical seatings, which enable them to adjust themselves to the shaft, and thus avoid the friction which inevitably arises with rigidly fixed bearings unless they are set absolutely in line.

The commutator of a dynamo is the part most subject to wear and deterioration, and the life of a commutator, supposing it to be well made at the start, depends almost entirely upon the adjustment of the brushes, which should be set so as to avoid sparking, press heavily enough to insure reliable contact, and yet not so heavily as to wear themselves or the surface of the commutator, at an undue rate. Hence it becomes necessary to afford effective means for readily adjusting the brushes of a machine, even while it is running, and it is safe to say that no better brush-holder than that employed on the machines just described has yet been designed. The distinctive feature of this holder is a feed-screw, which admits of each brush being fed backwards or forwards, in a direction parallel to its length, merely by turning the screw-head; an operation which usually necessitates the releasing of a clamping screw, which is tightened up again after the brush has been shifted. This brush-holder is illustrated in fig. 180, a side view being shown to the left, while the right-hand illustrates the holder as viewed from the back. The upper portion of the rocking bar is shown at A; this rocking bar is carried on a collar which forms an extension of the pedestal at the commutator end of the machine, and which is shown at *r* in fig. 179. By means of the handle H, both the upper and lower sets of brushes can be rocked round together, through a considerable angle, until the position of no sparking is found. A horizontal spindle, S, passes through the rocking bar; it is insulated therefrom by the vulcanised fibre collar and washers *a a*, and rigidly clamped thereto

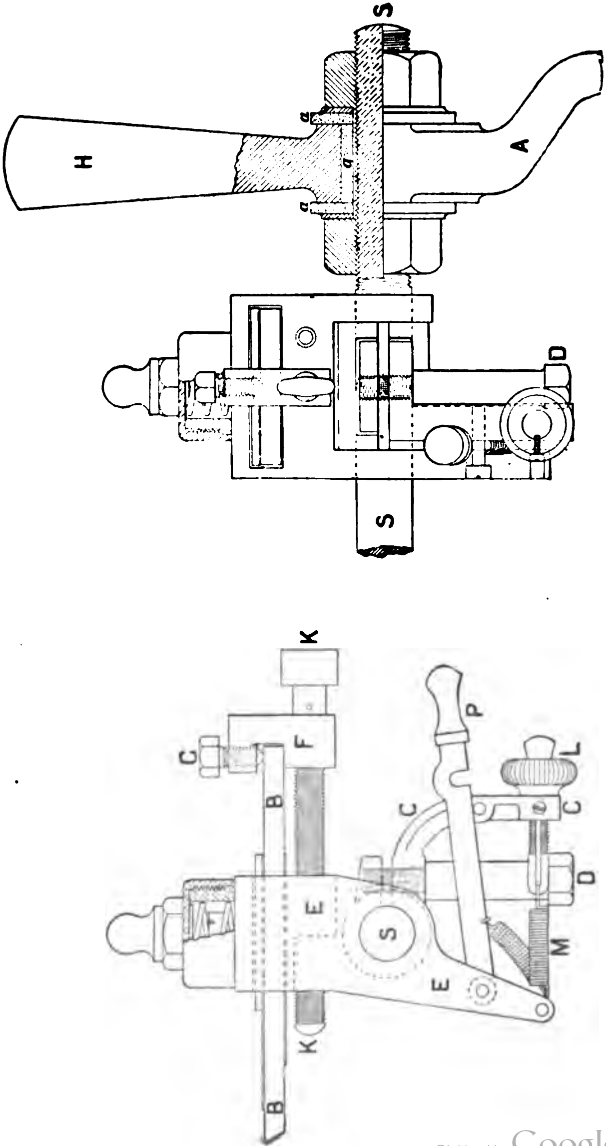


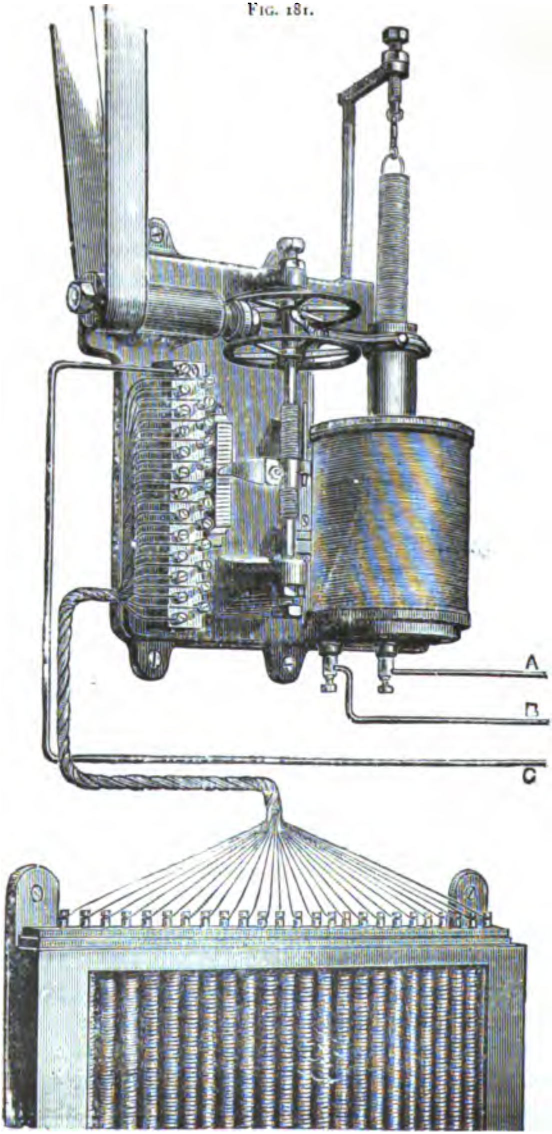
FIG. 180.

by a steel nut and washer on either side. A small bracket C C is rigidly fixed on the spindle S, by means of a screw D, and a second bracket E E rocks freely on the spindle. This latter bracket carries the brush B, which is clamped between two thin stiffening plates, and a spiral spring, pressing down upon a third thicker plate, holds the brush firmly in position, while it at the same time allows the brush to slide backward or forward. The end of the brush remote from the commutator is fixed in a small holder F by means of a set screw G; the feeding screw K passes through and bears against this small holder, while the thread of the screw works in the movable bracket E. It follows therefore that when the feeding screw K is turned to the right, the brush is fed forward through the bracket E, while it is brought backward by turning the feeding screw to the left, this sliding motion being entirely independent of any other adjustment. The actual pressure of the brush on the commutator is regulated by turning the milled nut L on a small screw which passes through the lower end of the fixed bracket C. The screw is slotted to receive a small set screw fixed in the bracket, which prevents it turning, and the end of the screw carries a spiral spring M, the other end of which is fixed to the lower extremity of the movable bracket E. By turning the milled nut to the right the tension on the spring M is increased and the pressure of the brushes on the commutator made greater, and *vice versâ*. The holding-off catch P enables the brush to be lifted from the commutator and held away therefrom. In order to effect this it is pushed forward until the slot engages with the pin on the bracket C; the upper end of the movable bracket E is thus forced backward, carrying the brush with it.

The two dynamos described are compounded. The object is to give a constant potential when driven at a certain speed, but for cases where the speed is liable to variation, and where, therefore, a compound machine cannot with advantage be used, but where a constant potential difference is required, or where it is desired to maintain a constant current although the external resistance varies, an automatic mechanical regulator is employed. This regulator varies the strength of the field by altering the strength of the current flowing through the field-magnet coils. A set of resistance coils is placed in series with the field-magnet coils of a shunt-

wound machine, and an arrangement adopted for cutting out some of these coils when the current or the potential difference falls too low, or inserting more of them when it becomes too high. The complete set of regulating apparatus is shown in fig. 181. The resistance coils, which are shown at the lower part of the figure, consist of spirals of bare iron wire, supported by a wooden frame in such a manner as to afford great facilities for cooling when heated by the passage of the current. An important part of the apparatus is the large solenoid, placed with its axis vertical. If it is desired to maintain a constant potential under varying conditions, this solenoid consists of many turns of fine copper wire, the two wires A and B, leading from its terminals, being joined to the brushes of the dynamo. An iron core, suspended by a spiral spring, enters a short distance into the upper portion of the solenoid. When the potential rises the current increases and sucks this core further down; while a fall of potential allows the antagonistic spiral spring to withdraw the core a little. From the upper portion of the core projects an arm, its end playing between two light wheels which are rigidly fixed on a common vertical spindle, this spindle having a small amount of end-play. The tension of the spring is so adjusted that when the potential is at the required value the upper wheel just rests upon the arm projecting from the core, and both wheels are kept clear of a small rubber-faced disc on the end of a short horizontal shaft, which is driven by a belt from the main shafting. If, on account of a rise in the potential, the core with its projecting arm is sucked down, the two light wheels drop, and, the upper one engaging with the rubber disc, is rapidly rotated. A screw thread is cut in the vertical spindle some little distance below the wheels, and on it is a rather long screw-nut which is prevented rotating, and which, therefore, travels up or down according to the direction of rotation of the vertical spindle. A flat spring projects from this nut, its end passing over a set of contact pieces to which are connected the various resistance coils, one end of the series of coils being joined to the upper contact piece, and the other end direct to the vertical spindle and screw nut, which are also in connection with the terminal B. The arrangement is such that the motion imparted to the spindle, due to an increase of E.M.F., moves the flat spring in the direction

FIG. 181.



which throws more resistance in series with the field-magnet coils, while if the core is moved upwards the lower wheel engages with the friction disc and rotates the spindle in the reverse direction, reducing the resistance in the field-magnet circuit.

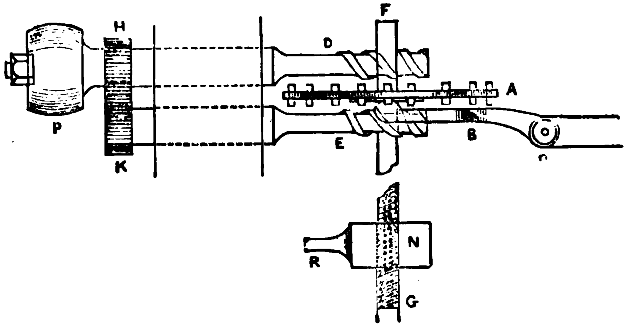
The solenoid is subject to the same heating error as a voltmeter, and to minimise this it is more frequently wound with fairly thick wire, the temperature of which rises but little, and the necessary resistance is obtained by joining in series with it German silver coils, which have a lower temperature co-efficient, and which, being left bare, dissipate heat readily.

When the apparatus is required to maintain a constant current, the solenoid is wound with thick wire, and is joined up directly in the main circuit; the rise and fall of the main current which passes through it acting in the same way as a rise and fall of potential at its ends. The small horizontal shaft is driven at about 400 revolutions per minute, and the nut carrying the contact spring can then travel over the whole range in about ten or twelve seconds. The flat spring is so broad that the circuit is never broken during the movement of the spring, and a large number of coils is employed in order that the increase or decrease of the resistance shall take place gradually. The weak point about the apparatus, as depicted in fig. 181, is the means adopted for imparting circular motion to the light wheels; for, although the friction between the rubber disc and the wheel rim is at first quite sufficient, it becomes uncertain and unreliable if the rubber gets dirty or covered with oil. To overcome this difficulty an entirely different gearing has been adopted in the later apparatus, the essential parts of which are shown in fig. 182. R is the contact spring, carried by the nut N, working upon the screw shaft G, up or down which the nut travels according to the direction in which the screw is turned. The screw forms the lower part of the vertical spindle F G, upon the upper part of which is fixed a pin-wheel A, that is, a flat disc having a number of pins fixed parallel to its axis at equal distances round its circumference. Behind the spindle and parallel to the plane of the disc are two endless screws D, E, the upper one being at the end of the shaft, which is driven by a belt on the pulley P. By means of the equal spur wheels H and K, the lower shaft is driven at the same velocity as the upper one, but in the opposite

direction. The arm projecting from the top of the core of the solenoid is pivoted at C, and forked from the point B, the adjustment, as before, being such that when the current or potential is at its proper value the pin-wheel rests on the extremities of the fork, just midway between the two revolving screws. Any movement of the core raises or lowers the supporting arm, thus lifting the pin-wheel or allowing it to fall, so that the pins then gear either with the upper or the lower screw, and communicate a circular motion to the vertical spindle in the one direction or the other as the case may be.

Within certain limits, the E.M.F. or current which the regulator maintains can be varied by altering the tension of the spiral

FIG. 182.

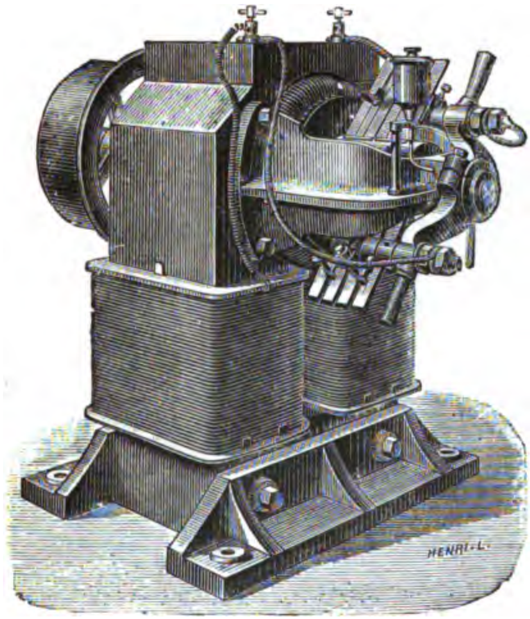


spring (fig. 181), and as this spring is a very important factor in the smooth working of the apparatus, considerable care is exercised in selecting it. In order to render the core perfectly astatic, resting decidedly in any required position, it is necessary for the pull of the solenoid on the core and the antagonistic pull of the spring to balance each other, length for length, throughout the whole of the space travelled by the core—that is to say, suppose it experiences a sucking force which moves it two centimetres inwards, against the spring, the force of suction on the core in this new position must be greater by exactly the same amount that is necessary to extend the spring two centimetres. This rather difficult adjustment is so successfully accomplished that the core is per-

fectly astatic, gliding to any new position immediately the current changes, and floating there without any oscillation.

The 'Phœnix' dynamo is made by Messrs. Paterson & Cooper and in two distinct forms, according to the circumstances under which the machine is to be employed. Where lightness of construction is imperative the field-magnets are made of wrought-iron, but where the weight becomes a matter of secondary import-

FIG. 183.



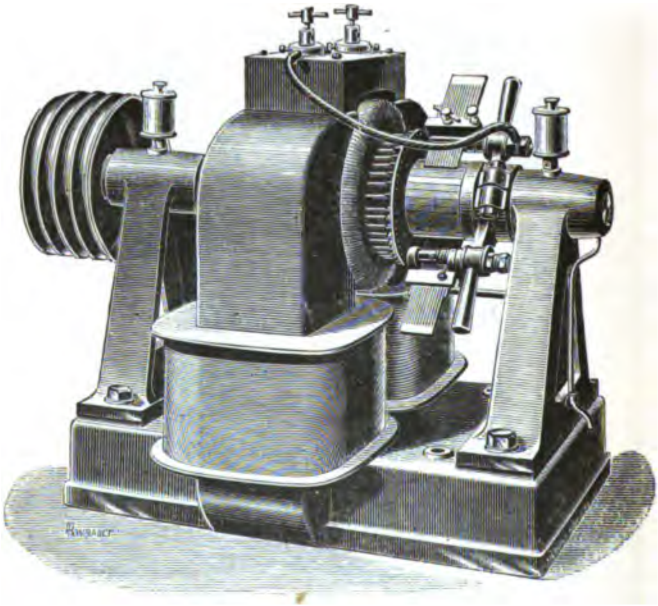
ance cast-iron is used, its lower permeability being compensated for by using about two and a half times the amount of metal. The first of these machines, in which the aim has been to obtain a comparatively great electrical output for a minimum weight, is illustrated in fig. 183.

The field-magnet and bed-plate are the parts of the machine in which the greatest reduction in weight can be made, and it will be observed that this reduction in weight is accomplished

without increasing the magnetic resistance or diminishing the mechanical strength.

The field-magnet is of the horse-shoe shape, fixed with the poles uppermost. It is made of a single massive wrought-iron forging, which is slotted out to form the two limbs, sufficient metal being left at the bottom to form a substantial yoke. The space in which the armature revolves is then bored out. It will thus be

FIG. 184.

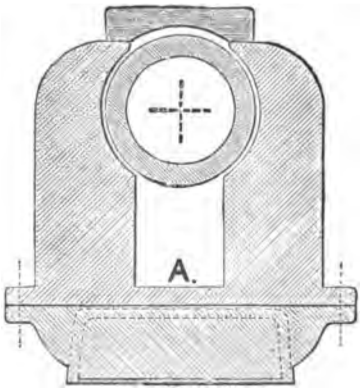


seen that there is no break in the magnetic circuit, while, being of wrought iron, the magnetic resistance is very low. Two cast-iron angle-pieces, which receive the foundation bolts, are bolted on to the yoke. The bobbins on which the field-magnet coils are wound are made of sheet-iron, with brass flanges, and are slipped over the limbs after the wire has been wound.

Two very strong gun-metal brackets are then bolted to the pole-pieces, for the purpose of carrying the armature bearings,

which are of white metal, the whole forming a machine mechanically strong, but of comparatively little weight. It need hardly be said that this construction is somewhat expensive, and would not be warrantable in cases where there is a solid foundation available and where a little extra weight is immaterial. Fig. 184 illustrates a machine designed for use in such cases, a section through the field-magnets being shown in fig. 185. Here the field-magnets are of cast-iron, but of greater sectional area. Both limbs are in one casting, being connected together by the rather thin piece shown at A. This casting is securely bolted down to the cast-iron bed-plate, which, directly underneath the field-magnet, is solid and massive, and, together with the thin connecting-piece A, forms the yoke. The terminal board is fixed across the upper ends of the field-magnet cores. The bobbins are similar to those in the machine previously described, but the armature is carried on cast-iron standards bolted to the bed-plate. In the machine shown the pulley is grooved for rope-driving.

FIG. 185.

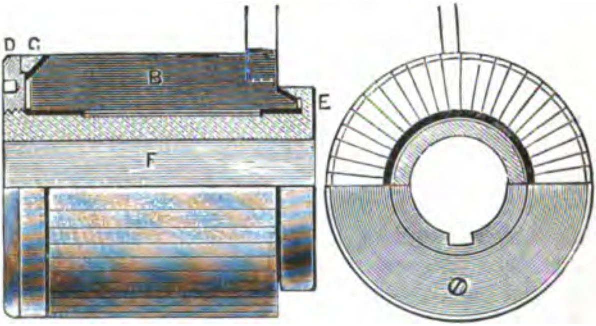


The commutator consists of forty-eight bars, of hard-drawn copper, insulated with mica. Fig. 186 gives two views of this commutator, the upper half in each case being shown in section. Upon the steel shaft F is keyed a gun-metal bush, E, with a rim at one end recessed to receive the projections from the commutator bars B. The opposite corner of these bars is shaped to fit a steel ring, C, of triangular section, which is held tight home by the wrought-iron nut, D, screwed on to the gun-metal bush. The bars are insulated from the bush E and ring C by sheets of white fibre, indicated by the thick lines in the figure.

The armature is of the ring type, and its core is built up of a number of thin soft iron rings (D, fig. 187), insulated by paraffined paper, and the whole firmly clamped together between two end

frames by three delta metal bolts, B, semicircular pieces being stamped out of the iron rings to fit these bolts. A gun-metal spider with three radial arms, G, is keyed on to the shaft at each

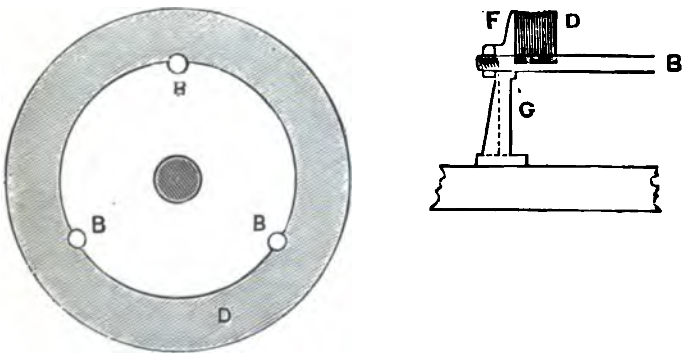
FIG. 186.



end of the core, the bolts passing through the extremities of the arms as at F.

One size of the machine illustrated in fig. 184 has an output of 6,500 watts at 100 volts (65 amperes) when driven at 1,300

FIG. 187.

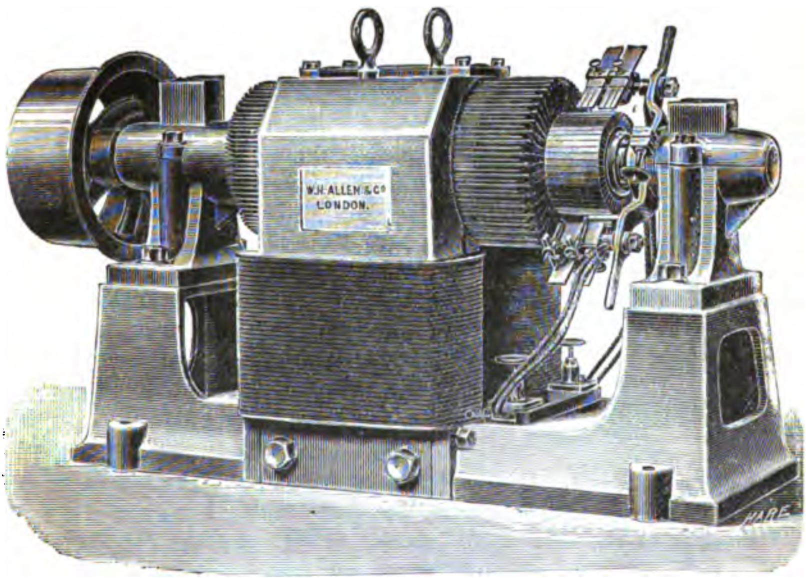


revolutions per minute. It is compound-wound. The resistance of the armature is 0·03 ohm, and of the shunt coil 20·68 ohms, the series-turns being wound inside the shunt coil and having a

resistance of 0·018 ohm. From these figures the student can calculate the power spent in the various portions of the circuit when the maximum current of 65 amperes is flowing.

A general view of a dynamo designed by Mr. Gisbert Kapp and constructed by Messrs. W. H. Allen & Co. is given in fig. 188. The field magnets are also of the inverted horse-shoe pattern, but the armature in this case is of the drum type.

FIG. 188.



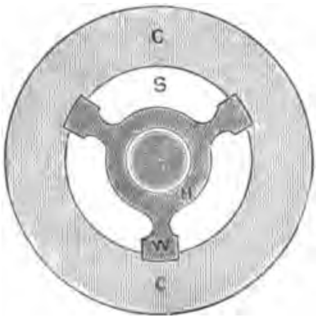
Figs. 189 and 190 illustrate many details of the machine, the former being a longitudinal section, and the latter an end view, half in section.

Each field-magnet limb, F, consists of a single slab of wrought-iron, the lower end of which fits into a slot in the cast-iron bed-plate. The bed-plate is solid at this part, and the vertical limbs are secured in position by two large bolts passing through, as shown in fig. 190. The pole-pieces are bored out circularly to

form the space in which the armature is to revolve, and the pole-tips *a a* securely pinned on. Upon the upper pair of pole-tips is fixed a board B, which acts as a cover to protect the armature. The field-magnet coils are of cotton-covered copper wire, and are wound on frames or bobbins of thin sheet steel, *b b*, insulated with varnished paper, the bobbins being slipped over the cores after the wire has been wound, and before the pole-tips *a a* are fixed.

The construction of the armature, which is well designed and built with extreme care, is shown in fig. 189. H is a cast-iron hub, having three radial arms, W; it is securely keyed on to the steel shaft, its length, with the arms, along the shaft being equal to the length of the finished core. The edges of the arms are planed to fit into notches in the core plates, C, as shown in fig. 191, which is a section through the armature core and hub taken at right angles to the shaft. The core plates are of thin charcoal iron, and between them at equal intervals are placed three pairs of thicker rigid plates, which are kept a little distance apart by pieces of hard fibre, thus affording spaces for the circulation of air for ventilating purposes. The core is built up with thin paper sheets separating the plates, and while under high pressure between temporary end-plates, the core is slotted to receive the arms, W, of the hub. The lettering of figs. 189 and 191 corresponds. In the former, one arm, W, is shown directly below the shaft, while above it is the air-space, S, between the other two arms.

FIG. 191.



At one end of the shaft is provided a solid boss, K, and against this bears a cast-iron plate, P, in which are inlets, D D, for the passage of air. The core is held between P and a similar end-plate, R, which is secured by a steel nut, N, screwed on to the shaft. The ventilation is thus most efficient, for the air can enter through each end-plate by openings similar to D, and find its way along the spaces, S, between the hub and core plates, leaving by the openings between the rigid plates previously referred to.

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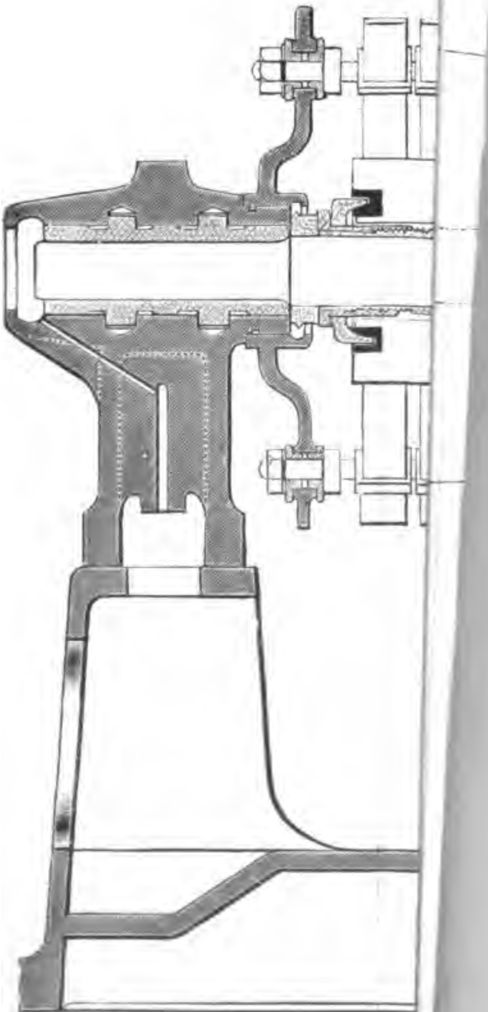
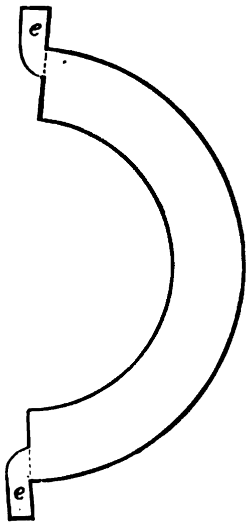


Before being wound the core is turned in a lathe to obtain a perfectly cylindrical and smooth surface. At intervals round the thicker plates there are projections, which serve to drive the conductor and prevent its being stripped. These projections are shown on the middle pair of plates in fig. 189, and, in addition to these driving horns, the completed armature is bound round in several places with thin strong wire, which effectually overcomes any tendency towards bulging or stripping.

There are 204 active conductors round the periphery of the armature, each consisting of a straight strip or bar of copper, 0·0215 sq. in. in sectional area, insulated with a double cotton covering. They project to different distances over the edge of the core, and are soldered either to the lugs which project at right angles to the ends of the commutator bars or to the ends of peculiarly shaped copper strips which form the cross connections.

FIG. 192.



One of these connecting strips is shown in fig. 192. It is a stamping of sheet copper, and forms almost, but not quite, a semicircle, because it is required to extend round the end of the armature just far enough to connect two bars which are almost at opposite extremities of a diameter. The connector is placed with its plane parallel to the plane of the core discs, and the two small end-pieces or tags, *e e*, are bent round at the part shown by the dotted lines until they are at right angles to the other portion of the strip. The ends of the two conductors which are to be joined together are soldered to these pieces (*e e*). For example, in fig. 189 the conductor A is connected to the tag *e*. The armature is divided into 51 sections, and each section consists of two convolutions, that is, four active conductors; the cross-connectors occupy a comparatively small space, a section through the whole of them being shown at L L. Over the shoulder of each end-plate is fixed

a cast-iron ring T, with a wide, deep groove in which the connectors are placed, each well insulated by being over-wound with tape treated with shellac varnish. There are fifty-one bars in the commutator, and the method of holding them in position is shown in the longitudinal section. They have two square notches, into which fit rings of hard vulcanised fibre, the sections through which are shown black in the figure, and it will be observed that there is a deep groove on the outer side of each ring. A gun-metal sleeve is keyed on to the shaft, one end fitting into the groove of one insulating ring, while a thread is cut round the other end for a nut, which, when screwed up home, presses a gun-metal ring into the groove of the other fibre ring. The commutator bars are insulated from each other by mica, and each brush is divided into two independently adjustable parts, this being a better arrangement than one wide brush, which would probably wear unevenly and, in consequence, cause a considerable variation in the amount of surface contact. Further, when two brushes are employed, one can be lifted for a moment, or shifted to a better position without completely breaking the circuit, as would be the case if only one brush were used. The sectional view also shows the manner in which the rocking bar is carried round a groove at the end of the cast-iron standard, and the fixing of the horizontal brush spindles, which are insulated from the rocking bar by hard wood collars. Various other mechanical details are set forth in the drawings, but perhaps it should be mentioned that the radial lines round the outer edge of the armature in fig. 190 indicate the edges of the small pieces, *e e*, of the connectors. This machine is shunt-wound, and when driven at a speed of 680 revolutions per minute it develops a potential difference of 120 volts, its maximum output being 12,000 watts. The resistance of the armature when cold is 0·045 ohm, and of the field-magnet coils 40·9 ohms.

Some details concerning a compound-wound machine having a somewhat greater output, but similar in construction to the machine just described, may prove of service to the student. In this machine the charcoal iron discs which form the core are 0·022 inch in thickness, have a radial depth of $3\frac{1}{4}$ inches, and an outside diameter of $12\frac{1}{2}$ inches, the core when built up with paper insulation being 20 inches in length. The wrought-iron slabs

which form the field-magnet cores are $19\frac{1}{2}$ inches by $7\frac{1}{2}$ inches in section, and the diameter of the opening bored out in the pole pieces to receive the armature is $13\frac{21}{32}$ inches. The drum-wound armature contains 102 active conductors, and the commutator has 51 segments, so that there are two active conductors forming, with a cross-connector at either end of the armature, one convolution per section. If the active conductors were solid copper bars they would be so massive that eddy currents as well as the main current would be induced in them, and power thereby wasted. In order to prevent these eddy currents the bars are laminated, each one being built up of six strips 0·29 inch by 0·054 inch in section; the strips are insulated from each other, and the built-up bar is twisted at the middle of its length through an angle of 180°.

The curved end connectors are $1\frac{1}{2}$ inch broad and 0·044 inch thick, and the resistance of the completed armature when cold is 0·075 ohm. The resistance of the shunt coils is 15·5 ohms, and that of the series coils 0·00111 ohm.

When driven at a speed of 550 revolutions per minute, the machine develops a potential difference of 110 volts, with a current of 550 amperes, the angle of lead of the brushes with this current being 10 degrees.

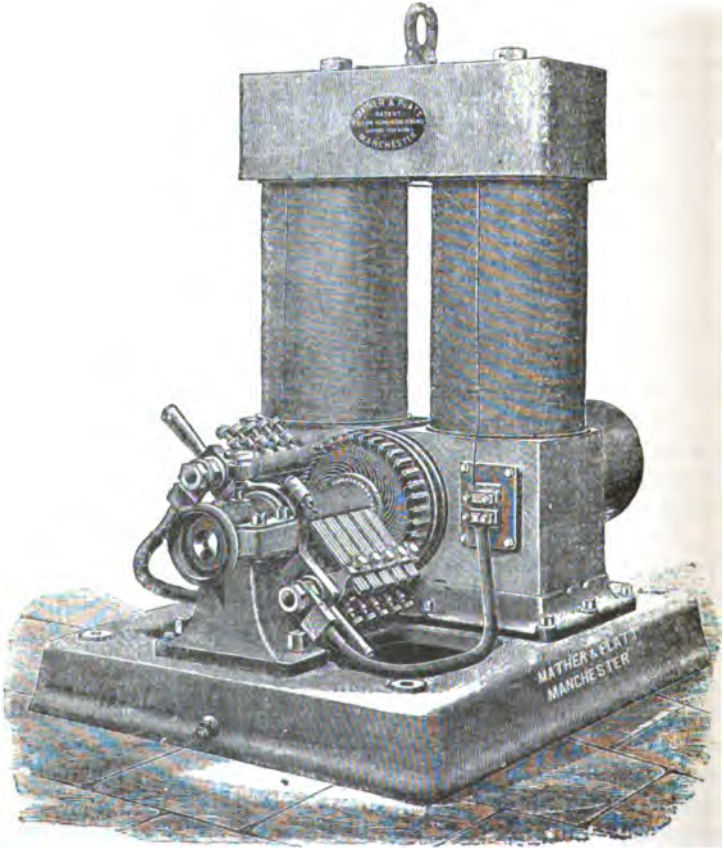
The value of N, or the total number of lines of force passing through the armature core, is 12,200,000, and the sectional area of the iron in the core being approximately 755 square centimetres, this gives a value for B of $\frac{12,200,000}{755}$, or about 16,000 lines per square centimetre.

On account of the efficient ventilation of the armature and other details in the design, the machine can be run for a lengthened period without any serious rise in temperature. The particular machine here described was run for six hours at full load, according to the test prescribed by the Admiralty, and at the end of that time the rise in temperature at the surface of the armature was found to be only 54 degrees Fahrenheit, and at the surface of the field-magnet coils 50 degrees.

In fig. 193 is illustrated the Edison-Hopkinson dynamo, which differs from the machines already described in that the armature

is placed at the lower ends of the field-magnet cores ; an arrangement which has the disadvantage that the iron bed-plate more or less magnetically short-circuits the pole-pieces, and affords a path

FIG. 193.



through which some of the lines of force leak, instead of passing through the armature. On the other hand, there is the advantage that the centre of gravity of the moving parts is kept low, thus adding to the stability of the machine; and also in some cases

affording facilities for driving direct from a steam-engine fixed upon the same bed-plate. In the machine under notice this leakage is reduced by interposing a massive slab of zinc between the pole-pieces and bed-plate. We will endeavour presently to see to what extent this is successful.

Each of the circular field-magnet cores, together with its pole-piece, is a single forging of wrought-iron ; the yoke is also of wrought-iron, rectangular in shape and very massive; it is secured to the cores by two bolts, the surfaces in contact being made to fit truly, so as to avoid, as far as possible, the introduction of any magnetic resistance. The armature-shaft bearings are of phosphor-bronze, and are carried by short cast-iron standards bolted on to the bed-plate. The armature is drum-wound, and its core is built up of thin discs, insulated with paper, and threaded on to the Bessemer steel shaft. Two thick, stiff end-plates hold the core-discs in position, one bearing against a washer which is shrunk on to the shaft, while the other is driven up tight by a large nut. There are forty sections in the armature of the machine illustrated, each of one convolution, and the conductor consists of thick copper bars, insulated with prepared rubber tape, the cross connections being made with stiff copper strips. These strips, the outer set of which can be seen in the figure, are led round spirally to the segments of the 40-bar commutator in such a manner that a coil whose plane is vertical is connected to segments which lie near the horizontal, and, consequently, the diameter on which the brushes are set is nearly parallel, instead of at right angles, to the direction of the lines of force through the armature.

The machine illustrated is shunt-wound, the wire composing the field-magnet coils being rectangular in section, thus reducing the waste space between the adjacent convolutions. The terminals of the machine are fixed to boards mounted on the pole-cheeks, and the marked difference in the size of the massive conductor which carries the whole current from the brush-bar to the terminal, compared with the thinner shunt-wire which passes up the sides of the field-magnet coils, will be observed. When driven at 475 revolutions per minute, this machine, which weighs about 4½ tons, is capable of developing 52,500 watts (105 volts,

500 amperes), and on account of the extremely low resistance of the armature it is practically self-regulating through a considerable range. Each brush-holder carries five copper-wire gauze brushes, all adjustable independently, and by this means a sufficiently large bearing surface upon the commutator is obtained without introducing any difficulty in compensating for unequal wear, such as would arise if one undivided brush were employed.

Some shunt-wound machines of this type, built for Central Station work, are constructed to develop a potential difference of 410 volts. In each case the armature conductors consist of stranded copper bars, the armature resistance being 0·0117 ohm. The resistance of the shunt coils is 52·7 ohms, so that the current through these coils is $\frac{410}{52 \cdot 7} = 7 \cdot 78$ amperes. At a speed of 400 revolutions per minute the current developed is 590 amperes, representing an output of about 242 kilowatts. The weight of the armature is 2 tons 19 cwt., and of the whole machine 24 tons 8 cwt. When tested, the electrical efficiency at full load was found to be 97·2 per cent., and the commercial efficiency 95 per cent.

This type of dynamo is additionally interesting from the fact that it has been carefully studied and tested by the Drs. Hopkinson, the results having been published in various papers. The object was (*a*) to endeavour to gain such information as would enable the performance of a dynamo to be predicted, when its configuration and the various dimensions and qualities of the material employed (especially the iron) are known; and therefore (*b*) to enable any machine desired to give certain results at a certain speed to be designed with a greater degree of accuracy than had previously been obtained.

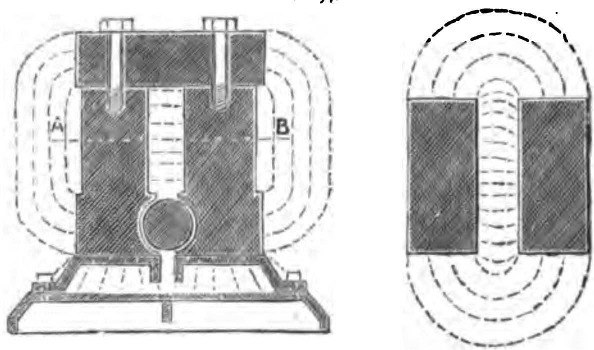
We know that in every machine the magnetising force required to develop the field in which the armature rotates is always in excess of that usefully employed; or, in other words, more lines of force are generated than actually pass through the armature core, the difference being caused by leakage at various points.

We will briefly describe one portion of the experiments with the view of enabling the student to better judge of the amount and locality of such leakage in any given machine.

The portion of the experiments referred to consisted, in the first place, of determining exactly the ratio of the lines of force generated in the field-magnet to the lines passing through the armature core. This ratio will of course always be greater than unity, and may be denoted by v.

In fig. 194, a machine with rectangular cores is shown in section, and lines of force are sketched to roughly indicate the principal paths of the leakage. Some of the lines pass directly from one limb to the other, others leak out between the yoke and the pole-pieces, while many pass down through the arched slabs of zinc (on which the pole-pieces rest) into the iron bed-plate.

FIG. 194.



We have previously mentioned that it is possible to compare the number of lines of force cutting or cut by a coil of wire in two or more given fields, by placing a galvanometer in circuit with the coil and observing the deflections. As the resulting E.M.F. is usually comparatively low, the galvanometer must be a delicate one, and it is usual to employ one in which a short strongly magnetised needle is suspended by a silk fibre inside a coil of many turns, the deflections of the needle being made evident by the movement of a beam of light reflected on to a scale by a small mirror fixed to the magnet. But in such a test it is necessary that the needle shall not begin to move or change its position until the whole of the brief current has actually passed through the coil, and it is preferable to make the needle short and somewhat heavy, avoiding as far as possible the introduction

of any damping effect. The number of divisions on the scale travelled over by the beam of light may then be taken as proportional to the E.M.F. developed, and therefore to the number of lines of force cut.

In the experiments under notice a current of 5·6 amperes was maintained through the field-magnet coils, from a battery, the armature being disconnected. A single convolution of wire was then wound round the middle of one limb as at B, the ends of this wire being joined to an instrument such as that just referred to, and known as a ballistic galvanometer. The needle being at rest, the field-magnet coils were short-circuited, thus suddenly stopping the current in them, and the lines of force, in collapsing, cut the single turn of wire and induced a current therein, which, passing through the galvanometer, deflected the beam of light for a moment. The needle having again settled itself steadily at zero, the short-circuiting connection was removed, thus once more suddenly passing the current through the magnet coils. The lines of force in springing outwards again cut the single coil, inducing a current which deflected the needle to an almost equal extent, but in the opposite direction to that produced by the first current. In this case the mean of the two deflections was 264 divisions, which, neglecting the small amount of residual magnetism, may be taken as proportional to the induction in, or the number of lines of force passing through, the field-magnet limb. The next step was to determine what proportion of these lines passed through the armature, which was of the drum type, each coil consisting of one convolution only.

The wires leading from the galvanometer were soldered one to each of two adjacent commutator bars, and the armature placed so that the plane of the coil connected to those bars lay at right angles to the lines of force.

The field-magnets were excited as before by a current of 5·6 amperes, and the deflection noticed, first when the current in them was stopped by short-circuiting, and again when the current was sent round them a second time; so as to suddenly withdraw lines of force from, and then to thrust them through the armature core. The mean of these two deflections was 200 divisions, and therefore

$$\frac{\text{Induction through field-magnets}}{\text{Induction through armature}} = \frac{264}{200} = 1\cdot32 = v.$$

That is to say, 24·24 per cent. of the total number of lines of force generated failed to reach the armature core owing to leakage. Although this method does not give us the actual number of lines of force in C.G.S. units, it nevertheless gives the proportion correctly, and in these experiments the actual number passing through the armature was estimated in C.G.S. units by running the machine at a known speed and measuring the resulting potential difference, without allowing a current to pass through the armature and distort the field. We have already given the formula

$$E = \frac{NPn}{10^8} \text{ volts,}$$

where N is the total number of lines of force passing through the armature, P the number of active conductors round the armature, and n the number of revolutions per second, and consequently in the experiment under consideration $N = \frac{10^8 \times E}{P \times n}$, where E is the observed potential difference in volts. Then the actual number of lines in any other part of the magnetic circuit could be found by simple proportion. Having shown that 24·24 per cent. of the lines of force were lost by leakage, the next step was to localise that leakage—that is, to discover at what points it occurred. This time the galvanometer, being less sensitively adjusted, gave a mean deflection of 115 divisions with one turn round the middle of one limb, when a current of 5·6 amperes through the field-magnets was suddenly stopped and started as before. Four convolutions were next wound round the bed-plate directly under the armature shaft, and, the current being stopped and started in the field-magnets, the galvanometer indicated a mean deflection of 50·25 divisions, due to the lines of force which leaked through the bed-plate and cut the four convolutions wound round it. Four turns were employed in order to get a fairly high deflection. The induced E.M.F. being, however, four times that which would be obtained with one turn, it becomes necessary, to enable this result to be compared with the previous one, to reduce it to the value of one convolution, thus:

$$\frac{50 \cdot 25}{4} = 12 \cdot 6 \text{ divisions, nearly.}$$

The leakage through the space between the field-magnet limbs was measured with a coil of ten turns wound on a square frame, and by a similar calculation was found to be proportional to eight divisions with one convolution.

The horns of the opposite pole-pieces approach each other both above and below the armature to within 12·7 centimetres, the depth of each being 8 centimetres. The leakage across each of these gaps was found to give 1·6 divisions, or 3·2 divisions for the two.

Reducing these losses to percentages of the total induction, we have

The leakage through the zinc plate and iron base	= 10·3	per cent.
The gaps between the horns account for	2·8	„
And the area between the limbs . .	7·0	„
Making a total loss accounted for .	20·1	„
Out of an observed loss of . . .	24·24	„

The leakage through the shaft, and from pole-piece to yoke, and from one pole-piece to the other by exterior lines, will account for the remaining 4·14 per cent.

The ratio, *v*, will of course vary slightly with different exciting currents in the field-magnet coils, especially when the iron approaches the saturation point, because the permeability of the iron decreasing with the induction through it, while that of the air remains constant, the proportion of leakage will be greater. It is easy to give the current passing through the field-magnetic coils such a value, that the cores and yoke will be magnetised to the same extent as when the machine is fully loaded, but to make the result accurate the armature should also be running and carrying its maximum current. Under these circumstances the leakage would undoubtedly be somewhat greater, as the permeability of the armature core would be reduced, and the demagnetising effect due to the heavy armature current would also tend to increase the leakage.

These experiments constituted the first definite attempt to discover the extent and the locality of the leakage of lines of force generated by the current in the field-magnet coils, and it will be seen that almost a quarter of the power spent for the purpose of developing the field in this particular case was wasted.

It should be remembered, however, that as the whole of the power expended in maintaining the field represents but a small fraction of the total power developed by a well-designed machine, this comparatively large percentage of waste field does not reduce the total efficiency to such an extent as might be at first sight supposed. The ratio $v = 1{\cdot}32$ found for this particular machine may be taken as approximately the value for most modern machines. Thus Mr. Esson found an exactly similar value for a Phœnix dynamo with a ring armature somewhat similar to that shown in fig. 184, while, according to Mr. Mordey, a Victoria dynamo similar to that illustrated in fig. 206 gave $1{\cdot}40$ as the value for v. In the Edison-Hopkinson machine the low magnetic resistance of the drum armature and the massive cores and pole-pieces bring the leakage to a low value in spite of the proximity of the bed-plate.

The value of the co-efficient of leakage v being approximately the same for all machines of similar pattern, it is usually employed in designing other machines of different sizes, and the following considerations will serve to show the manner in which it may be so employed.

Suppose in the case of a machine such as that shown in fig. 193 it be desired to calculate the number of convolutions of and the strength of the current which must be maintained through the coils (that is to say, to calculate the ampere turns) in order to project a certain number of lines of force N through the armature. We have already seen that for any simple magnetic circuit

$$N = \frac{M}{R}$$

where N represents the total number of lines of force, M the magneto-motive force ($\frac{4\pi}{10}$ or $1{\cdot}2566$ times the ampere turns), and R the magnetic resistance of the circuit. Consequently

$$M = N \times R;$$

that is to say, the requisite magneto-motive force may be found by multiplying together the total number of lines of force required to be produced and the magnetic resistance. In the case of the dynamo under consideration, the magnetic circuit is made up of

three distinct sections (see p. 219)—viz. the armature core, the two air gaps, and the field-magnet core, pole-pieces and yoke—and in order to obtain N lines through the armature, v N (in this instance 1·32 × N) lines must be urged through the field-magnet cores. If R_1 R_2 R_3 represent respectively the resistances of the armature core, the two air gaps, and the field-magnet cores and yoke, then the value of the requisite magneto-motive force

$$M = N R_1 + N R_2 + v N R_3 ;$$

and as M is equal to 1·2566 times the ampere turns, the value of the ampere turns can be obtained by dividing the right-hand side of the equation by 1·2566.

Since the magnetic resistance of any magnetic circuit, or of any portion thereof, is proportional to the length and inversely proportional to the sectional area and the permeability, the values of R_1 R_2 R_3 may be stated in terms of the dimensions and permeability of the respective parts. In order to determine the permeability, the maximum number of lines per square centimetre, B, at which the armature and field-magnet cores are to be worked must be decided upon beforehand, and then, from the magnetisation curves for the particular kinds of iron employed, the permeability of the armature core μ_1 and of the field-magnet cores and yoke μ_3 can be obtained.

If l_1 represent in centimetres the mean length of the path of the lines of force through the armature core, and a_1 the area of the iron in the core, taken at right angles to the direction of the lines of force, then

$$R_1 = \frac{l_1}{a_1 \mu_1}.$$

In calculating the value of a_1 due allowance must be made for space occupied by the paper or other insulating substance separating the core discs.

Similarly, the magnetic resistance due to the two air gaps

$$R_2 = \frac{2 l_2}{a_2},$$

where l_2 is the distance between the surface of the armature coil and one of the pole-faces, and a_2 the area of one of the pole-faces. The length l_2 is, of course, multiplied by 2 because there

are two similar air gaps, but the area a_2 does not correctly represent the area of the path of the lines of force through the air gap to the armature, because they spread out somewhat as they leave the edges of the pole-faces, and enter the armature core over a rather greater area than that of the pole-face. This increase of area tends to reduce the magnetic resistance of the air gap, and should be allowed for. It has been found that, nearly enough for all practical purposes, the increase in area may be considered as a fringe round the periphery of the pole-face, the width of this fringe being equal to four-fifths of the distance l_2 (because, of course, the tendency to spread out increases with l_2), and this increased area should be inserted in the equation as the value of a_2. The permeability of air and of the copper wire occupying the space referred to as the 'air gaps' being unity, the permeability need not enter into the expression for the magnetic resistance of the air gaps.

The magnetic resistance of the field-magnet cores, yoke, and pole-pieces is

$$R_3 = \frac{l_3}{a_3\mu_3},$$

where l_3 is the mean length of the path of the lines of force from one pole-face to the other, a_3 the area of cross section, and μ_3 the permeability of the iron. In this case it is assumed that the iron of the field-magnet is uniform throughout, but as this is rarely the case, it is frequently necessary, in order to obtain accurate results, to treat separately the pole-pieces, yoke, and the limbs over which the wire is wound. The permeability and sectional area of each part can then be dealt with separately, as also the value of N, which on account of leakage is less in the pole-pieces and greater in the middle of the yoke than at any other part of the field-magnet. But assuming for simplicity that the iron of the field-magnet is uniform throughout, it is evident that the magneto-motive force required to project N lines through the armature may be written

$$M = N\frac{l_1}{a_1\mu_1} + N\frac{2l_2}{a_2} + vN\frac{l_3}{a_3\mu_3}.$$

The magneto-motive force so found would be sufficient to urge the requisite number of lines of force through the armature

in the absence of any disturbing effect due to the current in the armature itself. We know that when the brushes are set with absolutely no lead, the armature field is projected at right angles to that of the field proper, while, when the brushes are shifted forward, the current flowing in a few of the active conductors actually strives to set up lines of force in the opposite direction to those due to the field-magnets. This back magneto-motive force must be allowed for by adding to the field-magnet coils such a number of convolutions as, with the particular current flowing through them, will give a number of ampere turns equal to the ampere turns on the armature acting in opposition to the field.

A little reflection will show that the number of active conductors on the armature so acting in opposition to the field will be all those included in an arc subtended by the angle of lead taken on both sides of the zero point.

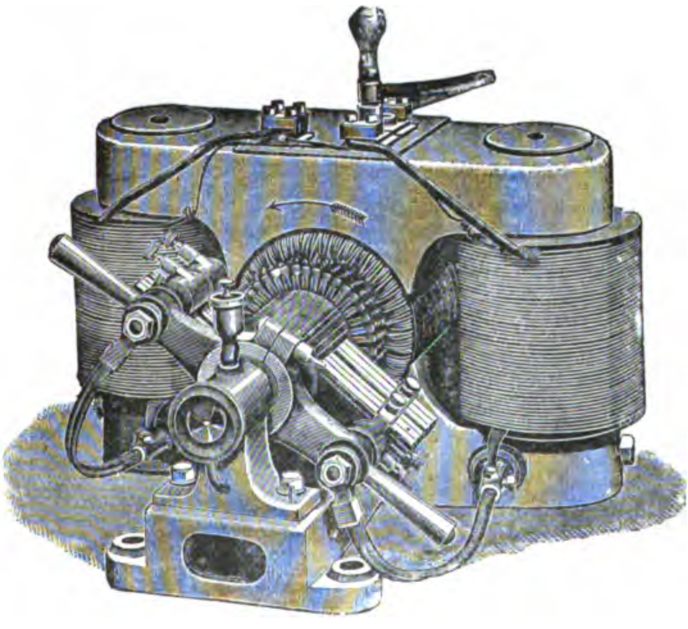
Suppose, for example, the lead of the brushes to be 8° and the number of active convolutions round the armature to be 180, then 8 active conductors, making up four convolutions, will be acting in opposition to the field. If the current flowing through the armature were 200 amperes, this would give $4 \times 200 = 800$ ampere turns setting up a back magneto-motive force. Consequently, if the current flowing through the field-magnet coils were four amperes, this would mean an addition of $\frac{800}{4} = 200$ convolutions to the winding of the coils of a shunt machine; while if the machine were compound-wound the necessary addition would be made to the series coils, because the back magneto-motive force, like the current in the series coils, increases with an increase of the load.

A fourth term representing this additional magneto-motive force should be added to the right-hand side of the equation given above. It will be $\frac{4\pi}{10}$ times those ampere turns on the armature which are opposing the field; and in any case in order to obtain the *ampere turns* required for the field magnet-coils, the right-hand side of the equation (which now represents the magneto-motive force) must be divided throughout by $\frac{4\pi}{10}$, which is equivalent to multiplying by 0·8.

A few other points which have to be taken into consideration in designing a dynamo are referred to in the various chapters in which machines are described.

The 'Manchester' dynamo, made by Messrs. Mather & Platt, is illustrated in fig. 195. The arrangement of the field-magnets differs somewhat from that in the machines hitherto described. Two electro-magnets are fixed vertically with their like poles

FIG. 195.

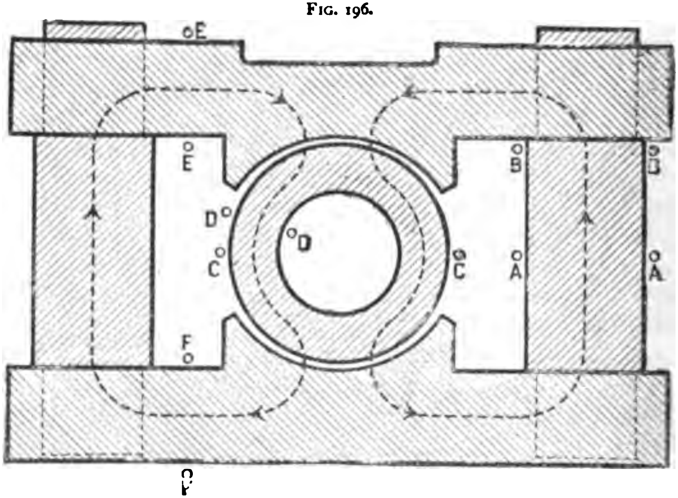


uppermost, the similar poles being in each case joined together by massive cast-iron yokes, shaped as shown, so as to form the pole-pieces between which the armature rotates. The lines of force due to the two field-magnet coils meet at the pole-pieces and pass through the armature in the manner indicated by the dotted lines in fig. 196. The vertical members of the field-magnets are of wrought-iron, let into the horizontal yokes, which, being of cast-iron, have about twice the sectional area of the cores. The lower

casting is extended on both sides so as to form the bed-plate of the machine, and the centre of gravity of the moving parts being low, it is comparatively easy to rigidly fix the machine so as to obtain great steadiness in running.

The shaft carrying the armature is made of Bessemer steel, the bearings being of gun-metal, and a free space along the shaft is provided to admit air for ventilating the armature. When driven at 1,100 revolutions per minute, the machine illustrated, which is compound-wound to maintain a potential difference of 100 volts, is capable of generating a current of 80 amperes, or a maximum

FIG. 196.



output at this speed of 8,000 watts. All other sizes of the Manchester dynamo are similar in appearance and construction to that shown in the figure, except that in the case of shunt-wound machines the heavy conductors for the series-winding are absent.

The commutator consists of forty bars of hard-drawn copper insulated with mica. Each arm of the rocking-bar carries two or more wire gauze brushes, each brush being independently adjustable for the reasons already explained. The diameter of commutation with machines of this class, in which the direction of the lines of force through the armature is vertical, approximates to the hori-

zontal, and this position in the Manchester machine is more nearly approached in consequence of a peculiarity in the curvature of the pole-pieces. Instead of the polar surfaces being made concentric with the armature, they are struck from a radius greater than that from the centre of the shaft, so that the pole-pieces are brought slightly nearer the armature at points opposite the extremities of its vertical diameter. The lines of force are therefore more concentrated at these places, which reduces the distortion, and, increasing the activity of the most active or vertical coils, decreases that of those near the neutral point.

The armature is of the ring type, the core consisting of the usual thin iron discs clamped between the ends of a gun-metal frame. The arms of this frame, which fit into slots in the discs, are free of the shaft, so that a clear space for ventilation is retained. The end-plate nearest the commutator is keyed to the shaft, while the other is held up tight against the plates by means of a nut. The wire is wound in forty pairs of coils, the resistance from brush to brush being 0·084 ohm.

The shunt coils on the field-magnet have a resistance of 41·5 ohms, and the series coils, which are wound outside the shunt coils, have a resistance of 0·049 ohm.

The gross weight of the machine is 10¾ cwt.

The brothers Hopkinson also made on this machine some experiments similar to those already described, and we may briefly refer to the simpler of the experiments which show the percentage and the locality of the leakage of the lines of force. Fig. 196 gives an outline of the field-magnets and armature core, and shows the various positions of the testing-coils. As in the other experiments, the armature was disconnected, and a constant current obtained from an independent source to magnetise the field-magnets, the lines of force being made to cut the testing-coil by suddenly starting and stopping the current in the field-magnets, and the mean of the two observed deflections of the ballistic galvanometer calculated as before. In the first experiment four turns were taken round the middle of one limb at A A, and the mean deflection was observed to be 214 divisions. But as with a single turn of wire only one-fourth of this would have been obtained, $\frac{214}{4} = 53{\cdot}5$ represents the total

induction through the field-magnet core in terms of the arbitrary unit here assumed. But an equal number of lines pass through the other vertical limb; therefore, the total induction through the field-magnet cores, as shown by this first measurement, may be represented by 107.

The coil was then raised to B B, where the mean deflection was 206, or, for a single turn, $\frac{206}{4} = 51 \cdot 5$, or 103 for the two limbs, and the mean of these two results—viz. 105—was taken as representing the mean induction in the field-magnet cores.

Three turns were wound round the armature at C C, where the deflection obtained was 222 divisions, or, for one turn only, $\frac{222}{3} = 74$, which represents the total induction through the space occupied by the armature. But we know that in a Gramme ring a certain number of lines pass diametrically across instead of round the armature core, which number becomes greater when the iron is so saturated that its permeability is low—perhaps lower even than that of the shaft—and the next experiment sought to determine the waste due to this cause. Four turns were taken round D D, the deflection being 141, or 35·25 in terms of one convolution. But as an equal number of lines pass through the other half of the ring, we must double this, getting 70·5 as the effective induction through the core, against 74 through the whole armature space and 105 through the field-magnets.

At E E 39·75 divisions due to one convolution were obtained, and, the induction being the same on the other side, the total induction = 79·5.

At F F the result was higher, being 41·75, or 83·5 for both sides, the difference being caused by the easier path at the bottom of the machine offered by the bed-plate and bearings, and, of course, these additional lines are wasted.

We see, therefore, that in this case a large number of the lines of force generated are wasted; in fact, here

$$v = \frac{\text{lines through field-magnets}}{\text{lines through armature core}} = \frac{105}{70 \cdot 5} = 1 \cdot 49 \text{ nearly.}$$

This loss is partly accounted for by the extension of the lower

yoke-piece to form the bed-plate, and the use of iron supports for the bearings, and is, no doubt, fully compensated for by advantages from a mechanical point of view. But it will be observed that almost 5 per cent. of the lines passing through the armature leave the core and pass diametrically across the ring; this

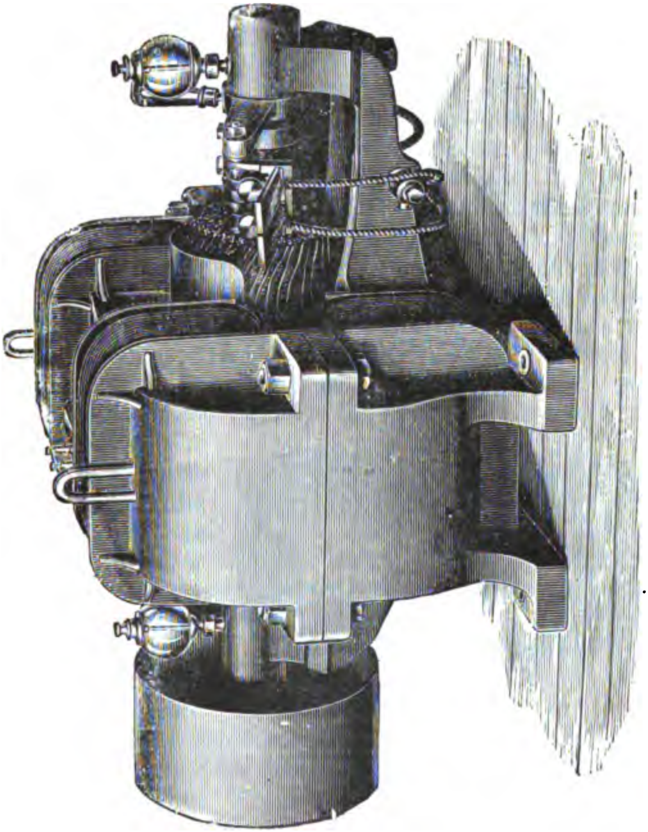


FIG. 197.

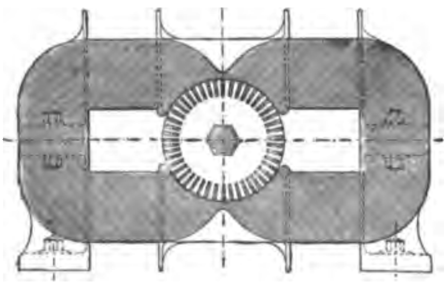
large proportion is, in a great measure, due to the fact that induction through the armature core was very high, viz. 20,000 C.G.S. units.

Another form of double horse-shoe magnet machine, and one

which differs considerably from any yet described in several important mechanical and electrical details, is that constructed by Messrs. Paris & Scott, and illustrated in fig. 197, a section through the machine being also shown in fig. 198. The field-magnets are of cast-iron, made in two parts firmly bolted together and provided with flanges to hold the four exciting coils, the lower casting having additional flanges to receive the foundation bolts. The armature shaft is supported by cast-iron brackets, provided with gun-metal bushes and bolted to projections from the lower pole-piece. The pole-pieces are bored out to form the armature space. The armature is drum-wound, but is furnished with teeth projecting between each of the sections, as in one of the earliest forms of armature devised by Pacinotti, whence these projections are known as Pacinotti teeth.

The chief objection to this type of armature core is that, although some of the iron is brought nearer the field-magnet poles, its uneven surface perturbs the magnetic field, keeping it in a state of oscillation and setting up eddy currents in the field-magnet poles. But in the machine under notice this effect is almost entirely obviated by employing a large number of teeth and making the distance between them very small, so that the oscillation of the field is very slight—indeed, practically imperceptible. One section of the armature is wound in each slot, which is just wide enough to take a single insulated wire, and deep enough to hold the number of wires in each section.

FIG. 198.



In the armature shown in fig. 198 each section consists of six convolutions, so that there are six wires in each slot. If the slots were made too deep, some of the lines of force would not be cut by the inner wires; in the present case, the number thus missed is very small, and practically none are lost in armatures having but two turns in each section. The core is built up of thin discs

of soft iron, of the shape shown in the sectional figure. The central holes are hexagonal, and the plates or discs are threaded on to the hexagonal steel shaft, so that each one is driven direct from it. This, added to the fact already mentioned that the wire is wound in deep and narrow slots, makes the armature as a whole mechanically strong, there being little risk of a sudden stress shifting the core or stripping the conductor from its place. There is an unusually large proportion of iron in the core; in fact, the whole of the space, except the small amount taken up by the insulating material, is occupied by the iron plates and steel shaft, no allowance whatever being made for ventilation. It will be observed, however, that a large amount of the iron core (the edges of the teeth) is in direct contact with the air, and as the armature rotates the heat is carried off by convection, thus preventing any great rise in temperature. The facility afforded in this way for the dissipation of the heat generated in the core gives to the Pacinotti ring one important advantage.

The commutator sections or bars are insulated with mica, rings of asbestos and fibre being employed at the ends of the bars to insulate them from the clamping-nut and washer by which they are held in position.

When the machine is compound-wound, the series-turns are usually wound on the top magnet cores. Should the series coil not occupy the whole of the wire-space, it is filled up with a portion of the shunt wire, which also occupies the whole of the space on the lower magnet cores. For large machines, sheet copper, insulated with strips of calico, is used for the series-winding.

The following details concerning one of these machines, constructed to give 12,000 watts at an E.M.F. of 100 volts when driven at 710 revolutions, will be of service.

The armature is wound in fifty-two sections, each of two convolutions, so that there are fifty-two bars in the commutator and two wires in each slot. The sectional area of the cast-iron field-magnet cores is considerably greater than that of the armature core, the former being 98 and the latter 29·7 square inches. The maximum magnetic induction through the armature core is about 21,000 C.G.S. lines per square centimetre.

The armature conductor is of braided wire, very carefully insulated from the core and from the adjacent wire in the same

slot, and the current density in the conductor, with 120 amperes, is 3,210 amperes per square inch.

The series-winding on each of the top limbs consists of twenty-eight turns of sheet copper, 4·5 inches wide and 0·025 inch thick, having a resistance of 0·0124ω, and giving, with the maximum current, 3,360 ampere turns.

The resistance of the shunt coils is 32·4ω, the ampere turns, with the potential difference of 100 volts, being 6,468.

We may from the above easily determine the number of watts expended in the various parts of the circuit, remembering that the amount developed in the external circuit when the maximum current is being obtained will be $E\,C = 100 \times 120 = 12{,}000$ watts. Thus,

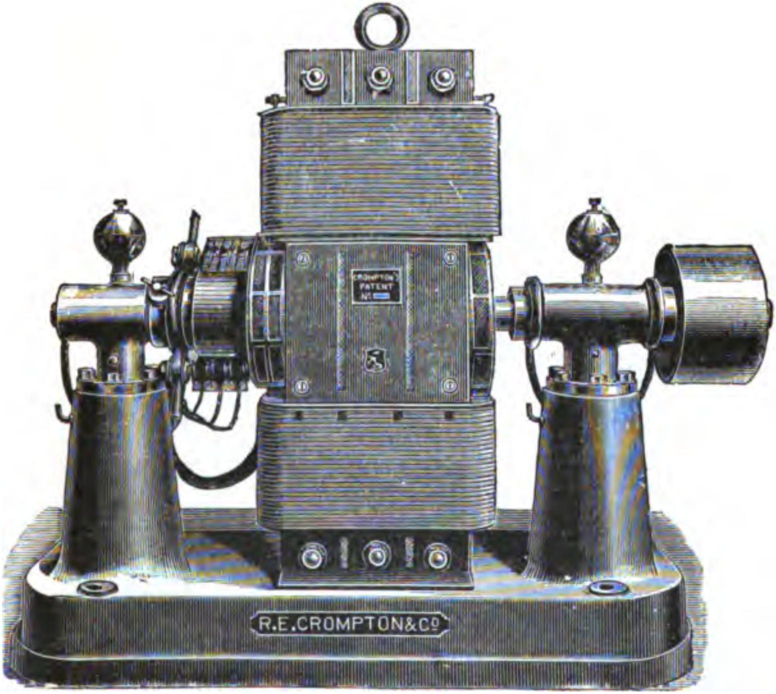
Shunt coils	32·4ω,	watts lost with	100 volts	=308
Series „	0·0124ω,	„ „	120 amperes	=178
Armature „	0·045ω,	„ „	120 „	=648

Fig. 199 illustrates the dynamo of Messrs. Crompton & Co. It is somewhat similar to the Manchester dynamo, and to that just described, in that it consists of a double electro-magnet, the difference being that it is fixed vertically instead of horizontally. The field-magnet cores are of annealed wrought-iron or of mild steel, and are fixed by bolts and nuts to the cast-iron bed-plates. The coils are wound on four bobbins, and connected in such a manner that the two coils on the same magnet-limb have their similar poles adjacent, the pair on the one side having their north poles and that on the other side their south poles adjacent, so that the lines of force pass horizontally through the armature from and into those portions of the vertical limbs between the coils, which portions therefore form the pole-pieces.

This machine is furnished with a ring armature, in which the iron discs are insulated by varnished paper. The steel shaft has four longitudinal grooves, into which fit radial bars of aluminium bronze, their length along the shaft being equal to the length of the core. The outer ends of these bars dovetail into notches in the discs. The conductor is of rectangular cotton-covered wire, wound in one layer on the outer circumference, but in two layers over the inner face of the core, which, besides being

smaller, is partly occupied by the radial driving bars. Insulated steel wedges project at intervals from the core, to drive the conductor on the outer circumference, and the armature is also bound over with thin tinned steel wire to prevent bulging. The brushes are carried on a gun-metal spindle, which is insulated by a fibre collar from the cast-iron rocking bar.

FIG. 199.



Several interesting types of dynamo are made by Messrs. Ernest Scott & Mountain, and one of these, fitted with a ring armature, is illustrated in fig. 200. Special attention is directed to the field-magnet, the construction of which is clearly shown in fig. 201. There is only one field-magnet coil, which is wound on a wrought-iron bobbin, and slipped over a cylindrical core of soft

wrought-iron of high permeability. This core is fixed in a horizontal position, its ends being turned down to fit into massive castings, which form the continuation of the field-magnet core, and also the pole-pieces. The core is made to fit into the castings accurately, in order to avoid as far as possible the introduction of any additional magnetic resistance at the joints, and the three pieces are securely held together by two circular steel nuts, which screw on to the extreme ends of the wrought-iron core as shown.

FIG. 200.

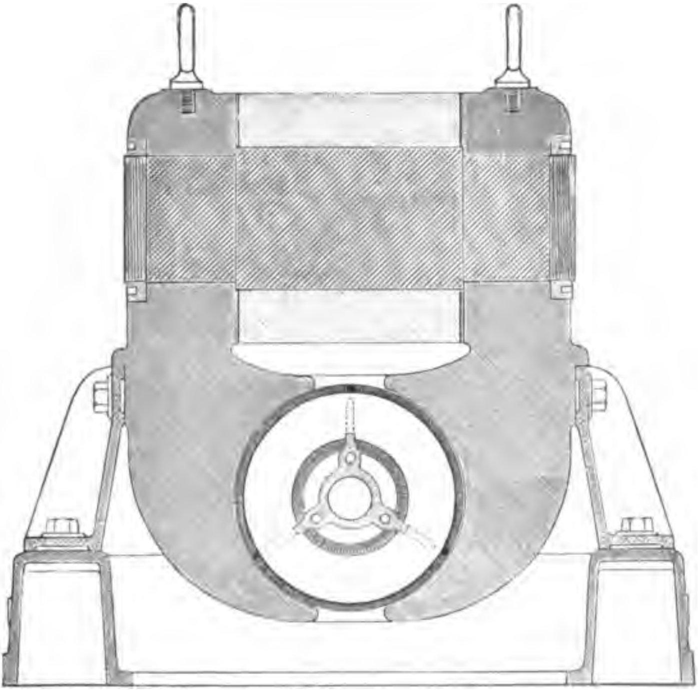
As the field-magnet is fixed with the pole-pieces downward, it is necessary to magnetically insulate it, as far as possible, from the cast-iron bed-plate, in order to minimise the leakage of the lines of force. This is effected by supporting the field-magnet on two strong gun-metal brackets, which are bolted to the bed-plate and field-magnet, as shown in figs. 200 and 201.

The spindle is of mild steel, the bearings being of gun-metal

lined with white metal; and it will be seen that the design is such that the centre of gravity of the moving parts is very low, thus securing freedom from vibration.

The sections given in figs. 201 and 202 illustrate the manner in which the armature is built up. The core-plates are of Swedish

FIG. 201.



charcoal iron, and a stout wrought-iron disc is placed at each end of the core. The plates are driven from the shaft by means of a gun-metal frame made in halves, and having three radial arms, with extensions at the ends. The edges of the arms fit into slots cut in the core discs, and the two halves of the frame are held firmly together by three steel bolts which pass though the arms. When the nuts on these bolts are screwed up, the extensions of the

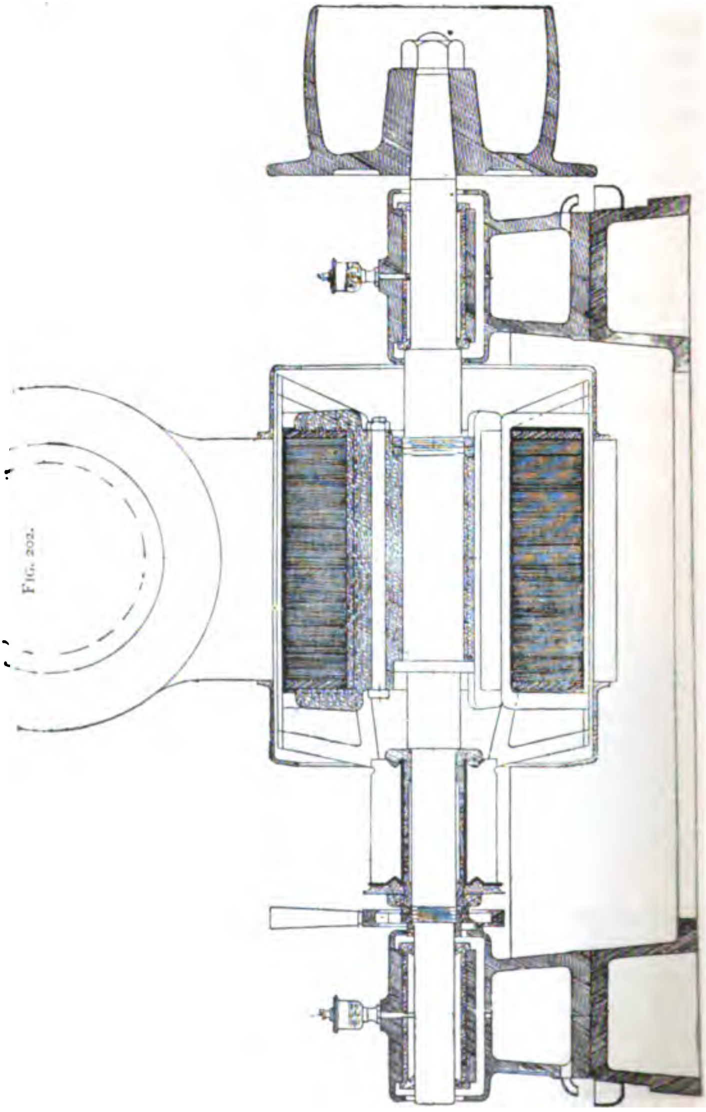


Fig. 202.

arms press against the stout wrought-iron end discs, and hold the whole of the core discs tightly in position. The gun-metal driving frame is keyed to the shaft, thus securing rigid driving; and one end of the frame bears against a hub on the shaft, two steel nuts being screwed up against the other end.

The construction of the commutator is shown to the left in fig. 202. A phosphor bronze sleeve fits over the shaft, and it is provided at the right-hand end with a flange, coned to fit into the ends of the hard-drawn copper segments, while a similarly coned washer fits into their other ends, the washer being clamped up tight by means of a circular nut.

It will be seen that the machine is compact, and that the design is simple and readily admits of good mechanical construction throughout.

The particular machine illustrated is shunt-wound, and when running at 750 revolutions per minute it is capable of maintaining a current of 380 amperes at a potential difference of 105 volts.

We have remarked that it is not possible in practice to 'compound' a machine to give a constant current in the same manner that a constant potential can be maintained. Hence a variety of other devices, mostly mechanical, have been suggested for the purpose, one of which has already been described, and we will now direct attention to a machine, designed and constructed by Mr. J. G. Statter, to maintain a constant current at a constant speed when the external resistance is varied; or when the speed is varied and the resistance remains unaltered; or, within certain limits, when both speed and resistance vary.

Although the machine has not been used to any considerable extent, it probably best represents its particular class, and the considerations involved in the design will prove instructive.

When an armature is rotated in a simple field, with the brushes removed from the commutator, there are two points, at opposite extremities of a diameter, at one of which the potential is a maximum (positive) and at the other a minimum (negative), and it is at these points that the brushes should be set in order to obtain the greatest difference of potential. From the negative to the positive brush, either way round the commutator, the potential gradually increases in value, and if the negative brush were shifted,

say, 20° forward, it would touch at a point of higher potential, and consequently the *difference* between the two brushes would be reduced. A like reduction would follow if the positive brush were moved forward, because it would then make contact at a point of lower potential; and in the third case the difference of potential between the two might be decreased by giving them simultaneously a greater angle of lead, until they would be at nearly the same potential when moved through an angle of 90°.

It follows that by merely shifting the brushes the potential difference at the terminals may be made what we please from the maximum downwards, and this method might be employed to vary the pressure, and therefore the current, to suit the requirements of the circuit. Thus the brushes might be set 20° ahead of their normal position of no sparking—that is, where the difference of potential between them is at a maximum—and then, if the current became too strong, the brushes could be shifted yet further ahead, thus reducing the potential difference and also the current; while by moving the brushes back towards their normal position the current could be increased in strength, should it fall below the desired value.

This would, however, be impracticable in an ordinary dynamo, on account of the terrific sparking which would ensue; and one of the principal features in the machine under notice is the method by which it becomes possible to vary the lead of the brushes through a considerable angle, without causing this sparking.

Confining our attention at present to the case of ring armatures, it will be remembered that when a coil which is carrying the whole of the current generated in one half of the armature is short-circuited by the brush, the electro-magnetic inertia of the coil, due to its self-induction, prevents the instantaneous cessation of the current; and that even if the coil is commutated at the moment when its plane is exactly at right angles to the field, and therefore in itself inactive, yet there will be a considerable spark caused by what we may term the self-induction current in the coil. For this reason it is found to be necessary to give the brushes a slight extra lead, so that the coil may begin to cut lines of force, and have induced in it an opposing E.M.F. sufficiently strong to just counteract this self-induction effect, and stop the current in

the coil before the brush leaves its commutator bars. Now, the weaker the field the greater is the extra lead required to obtain this opposing E.M.F. The extra lead also increases with the self-induction of each individual coil, while in the case of some armatures having but one or two convolutions in each section it is very slight.

It must be remembered that this *extra* lead is not due to the distortion of the field, but is simply required to prevent the spark which would otherwise result from the self-induction of the coils. Neither must it be forgotten that if the current is kept constant in strength, the E.M.F. thus required to be counterbalanced is the same whether the coil is short-circuited at 10°, 20°, or 30° ahead of the normal position. In an ordinary field the activity of a coil increases with such rapidity as it leaves the neutral position that the self-inductive effect is quickly over-balanced, and there is a remaining E.M.F. opposite in direction induced by the field in the coil, which is then competent to cause sparking.

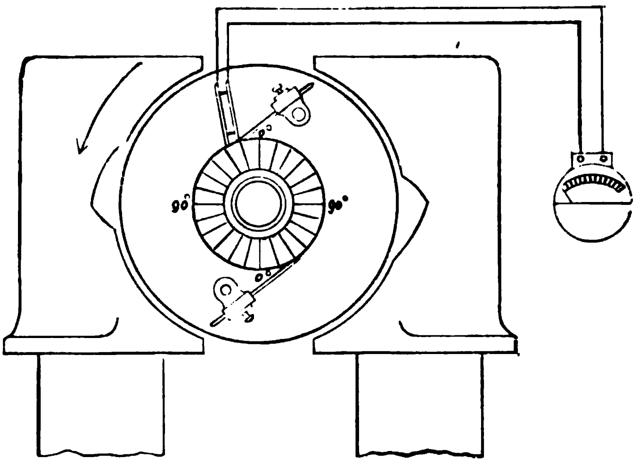
But if the field were made uniform and of such strength that for a certain distance beyond the neutral point—say through an angle of 40°—the number of lines cut by the coil at any position in that angular space was just sufficient to counterbalance the E.M.F. of self-induction, then the potential difference at the ends of the coil throughout that range would be *nil*, and no sparking would ensue if it were short-circuited.

This is Mr. Statter's method; and in order to allow a strong field to be employed, each coil contains an unusually large number of convolutions, there being also plenty of iron in the armature, so that a strong field is required to counterbalance the resulting high self-inductive effect. Portions of the pole-pieces are cut away at such points as will make the density of the lines of force entering the armature over a given angle uniform; and the exact places where the field has to be increased or reduced in strength are ascertained by experimenting in the following manner.

A series machine is constructed in the ordinary way, having pole-faces concentric with the armature, but with a rather larger number of convolutions than usual in each armature section. The speed at which it is driven is kept constant, and also the current,

say at 10 amperes, when the effect of self-induction, which has to be balanced, but not over-balanced, will be constant also. The first step is to find out what is the activity of a single coil at the various stages of its circular path, and, in order to decide this, use is made of a set of apparatus which has been employed for different objects by other experimenters with good results. It consists of a voltmeter of the requisite range, having its terminals connected by flexible wires to two copper strips, which are fixed at a sufficient distance apart by pieces of insulating material so that their ends bridge over the width of a commutator segment. The

FIG. 203.



arrangement of this simple apparatus and the method of using it are indicated in fig. 203. While the machine is running, and sending a current through an external resistance, the exploring brushes, as we may term them, are held against the commutator, as indicated in the figure, and each coil as it passes the point where the brushes are placed is connected for a moment to the voltmeter, which indicates the electro-motive force developed in the coils while passing that position. The exploring brushes are shifted by suitable stages round the whole of the commutator, and the deflection of the voltmeter noted for each position. The results are plotted in the form of a curve (see fig. 204), the

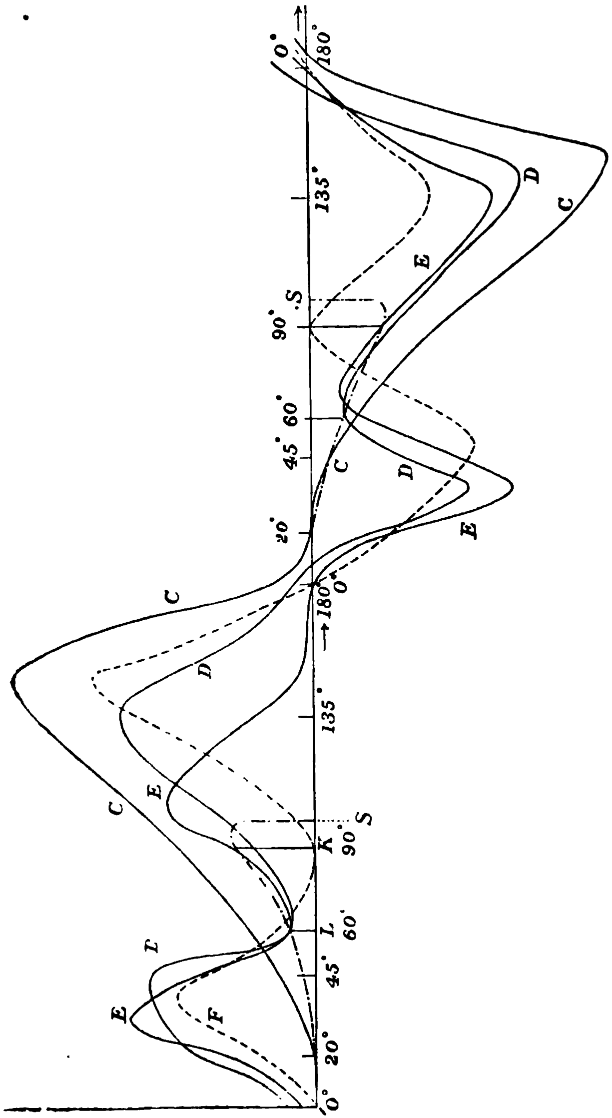


FIG. 204

distances along the horizontal line being taken to represent the angular distance of the coil from the zero position on the commutator, while the vertical distances represent the E.M.F. in volts developed by one coil in the various positions.

The curve C C was obtained in this manner when the main brushes were placed in the normal position, the lead being about 20°. The results obtained in passing *down* the commutator in the direction of rotation are plotted above, while those obtained in passing *up* are plotted below the line; and it will be observed that the E.M.F. at the extremities of each coil becomes *nil* at 20° from zero, while it is a maximum at about 150° from zero.

To facilitate comparison, both the point vertically above and that vertically below the centre of the shaft are regarded as zero points.

This curve having been obtained, the brushes were shifted forward to a position 60° from zero, and, regardless of sparking, the potential difference at the extremities of a coil in all the various positions was again measured. Another curve, D D D, was obtained by plotting these results, and it will be observed that, at the moment a coil is passing under the main brushes, the potential difference at its ends is considerable. This potential difference, which gives rise to the sparking, is in fact proportional to the height of the ordinate L, and it is equal to the excess of the E.M.F. induced in the coil by the powerful field at this point over the momentary E.M.F. due to the self-induction of the coil at the moment it is short-circuited. It is clear, then, that to eliminate the sparking when the main brushes are given a forward lead of 60°, the strength of the field must be reduced by just so many lines of force as would develop an E.M.F. proportional to the ordinate L, and then the E.M.F. of self-induction and that being induced in the coil would exactly balance. The length and number of active conductors in each coil, and also the speed of rotation, being known, this number of lines of force can readily be determined.

The main brushes were next given a lead of 90°, when, as might be expected, the sparking became even more severe, but by means of the exploring brushes and voltmeter the curve E E E was rapidly obtained. The E.M.F. in excess, which at this position of the brushes causes the sparking, is represented by the ordinate K,

which gives a means of estimating the extent to which it is here necessary to reduce the strength of the field. Ten such curves were obtained with the brushes in various positions between 20° and 100°; but we have only given three of them in order to avoid a complex figure. From each point on the horizontal line corresponding to the angular distance of the main brushes from zero, a perpendicular is erected to cut the curve which was obtained with those brushes in that particular position (as we have observed, L and K are such ordinates), and by joining the tops of the whole of the ten ordinates the dotted curves starting at 20° and terminating at S are obtained.

The area contained between one of these curves and the horizontal line affords an indication of the amount of iron which should be removed from the corresponding pole-face in order to weaken the field to the desired extent.

But since the very act of increasing the distance between the pole-face and the armature core at one point increases the density of the lines of force at another adjacent point, the areas only approximately represent the shape of the cavity required in the pole-face. For this reason the curves are, in practice, simply used as a guide to indicate to what extent the field requires reduction at the various parts, and the iron is removed to a rather less extent than is sufficient, so as to allow a margin for any error. Other curves are then obtained by means of the exploring apparatus, and a second approximation to the final result is arrived at, the process being again repeated if necessary. The dotted curve F was obtained with the brushes at 90° after the pole-face had been shaped, and shows by its coincidence with the horizontal line at 90° that no sparking took place with the brushes in that position.

One method of modifying the field is to cut a groove in the pole-face parallel to the shaft after the manner shown in fig. 203, and it will be seen that the outline of the groove approximates somewhat to the dotted shaping curves in fig. 204.

The desired result may, however, be obtained by removing the iron in a variety of ways, such as boring holes in the pole-pieces, or even by using iron of different permeability.

We have here considered the case of a ring armature machine

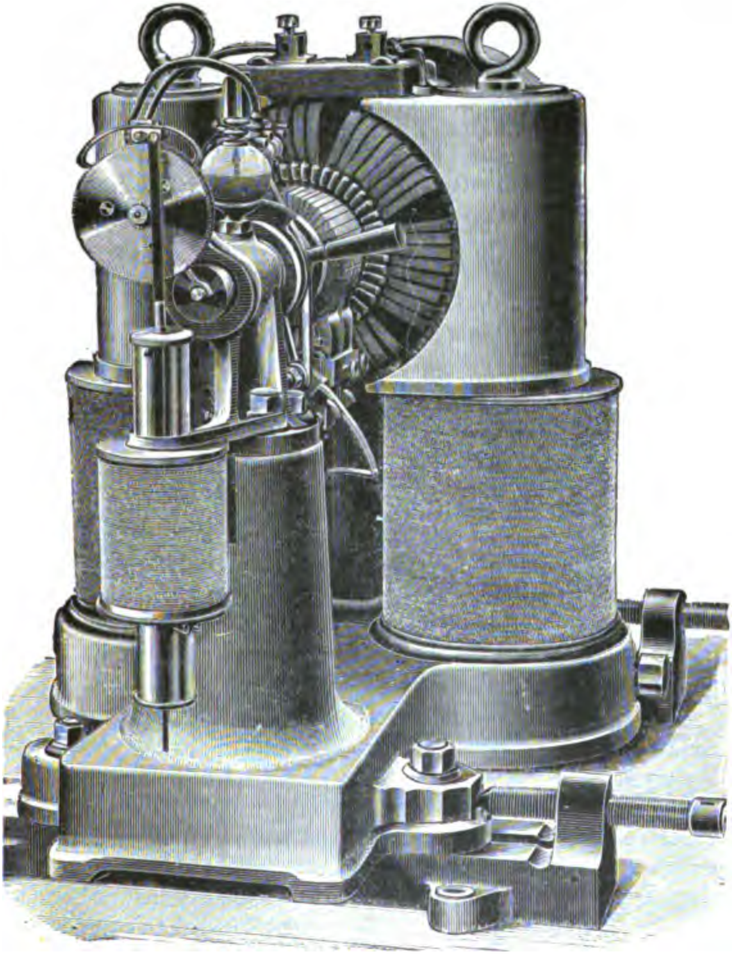
in which the maximum number of lines which each coil can at any one time embrace is only half the total number passing through the core. But in the case of a drum armature, the whole of the lines can at once be embraced and cut by a coil during half a revolution; it is therefore only necessary to 'explore' through 180° round the commutator, and plot the curves, say above the line, to obtain one shaping curve. This will indicate approximately the amount by which the whole field must be reduced, and the whole of the iron may be removed from one pole-piece, or half from each, as in fig. 203.

In this manner, then, is it rendered possible for the brushes to be shifted through a considerable angle in order to vary the potential difference, and maintain a constant current strength, without introducing sparking. It now remains to show the method by which the brushes are automatically moved to the proper position when the current tends to vary. A view of the machine, with its automatic regulator, is given in fig. 205. In this particular case two deep grooves are cut in each pole-face, but they do not extend to the pole-cheek, so that, in external appearance, it is similar to an ordinary machine. The solenoid shown in the front of the figure is wound with thick wire, and is joined up in the main circuit, so that the whole current passes through it. Inside it is a core capable of a small vertical movement, its centre being below that of the solenoid. When the main current rises above its proper value, this core is sucked up, and throws into gear a simple mechanism which increases the lead of the brushes and so reduces the current; similarly, a reduction in the current strength allows the core to fall, when the mechanism is reversed, and the brushes recede towards the zero or maximum-potential position.

The bar which carries the brush-holders is placed, as usual, on the end of the bearing next the commutator, the collar, however, being adjusted and the bearing oiled so that the bar can rock easily. On the upper part of the collar is fixed a toothed segment, which gears with a pinion on a spindle parallel to the main shaft; the other end of this spindle carries two ratchet-wheels, each $5\frac{1}{2}$ inches in diameter, but with their teeth set in opposite directions. The nearer of these ratchet-wheels can be seen in the figure; the other is but $\frac{1}{8}$ inch behind it, and the two

are rigidly fixed together by means of three set screws. When these wheels are rotated, the pinion at the other end of the spindle

FIG. 205.



on which they are fixed communicates the motion to the toothed segment on the brush-bar collar, and thereby slightly alters the

lead of the brushes, either forward or backward, according to the direction in which the ratchet-wheels are turned.

Above the wheels is a curved bar, with a pawl at either end; the pawls, however, are not in line, one being placed directly over and gearing with the front wheel, while the other gears with the back wheel. When the machine is running, the curved bar has given to it a continual rocking motion through a small angle, by means of a rod having at one end a slot, in which plays a pin eccentrically fixed on the end of the main shaft. In the normal state, the range through which the bar moves is such that neither pawl quite touches the ratchet-wheel directly under it, but by tilting the bar a little one way or the other, either pawl can be lowered sufficiently to gear with its wheel at every pulsation.

This tilting is given in the proper direction by the movement of the core in the solenoid, the core being attached to the curved rocking bar by a light rod, and, when the current becomes too strong and the core is sucked upwards, that pawl is thrown into gear which, step by step, gives to the brushes a forward moment, and *vice versâ*.

The large tube which, in the figure, can be seen passing right through the solenoid is rigidly fixed to it, and, in fact, forms the tube of the bobbin on which the wire is wound. It is made of brass, and inside it the core, which is a wrought-iron tube $1\frac{1}{2}$ in. in diameter, slides freely. The solenoid is 6 inches in length, and the iron core is a trifle longer, its centre being about 1 inch below the centre of the solenoid. Its play is limited to $\frac{3}{16}$ inch, so that it can only move just far enough to throw the pawls in gear.

The machine regulates remarkably well under the varying conditions previously referred to, the brushes steadily travelling backward and forward with but little sparking. The machine pictured in fig. 205 was designed to supply a constant current of 10 amperes to a number of arc lamps joined up in series, and is driven at 1,000 revolutions per minute. Any alteration in the number of lamps in circuit of course varies the external resistance, and the regulator immediately moves the brushes to compensate for this. With the maximum number of lamps joined up, the potential difference at the terminals is 1,290 volts, so that the power available in the external circuit is 12,900 watts. It is series-

wound, the resistances, measured when the wires were hot, being armature, 8·79 ohms; field-magnets, 3·3 ohms; regulating solenoid, 0·57 ohm. There are sixty commutator bars, and the number of convolutions in each section of the armature is fifty-four. The magnetic induction through the armature is rather over 17,000 C.G.S. lines.

A type of machine differing from those previously considered, in regard both to the armature and the field, is illustrated in fig. 206. It is known as the 'Victoria' dynamo, and is a development by Mr. W. M. Mordey of a machine originally designed by Schuckert. In the earlier days of practical dynamo-building, engineers were much exercised by the comparatively large proportion of wire on ring armatures which cuts few or none of the lines of force, and which, therefore, is called idle wire. The Schuckert machine was designed to minimise this as much as possible, by flattening the armature ring, and extending the pole-pieces so as to make them embrace more of the wire on the flattened sides of the coils. The arrangement did not, however, altogether answer the anticipations, for by merely extending the pole-pieces the density of the lines of force was diminished, and, with a magnet developing a certain strength of field, it matters little whether that field is spread out and the lines of force cut by a long piece of wire, or whether the field is more concentrated and cut by only a portion of the same wire.

This form of armature, even when the best shape is given to the pole-pieces, is in reality slightly less efficient than either the ordinary ring or the drum form, but it was nevertheless for a long time a favourite, chiefly because it offers good facilities for ventilation, is very light in construction, and (owing to the sectional shape of the armature coils) there is but little tendency for the wires to fly out when driven at a high speed. Flat ring armatures are also usually set to rotate in a 'multiple field'—that is to say, the field is generated by four, six, or sometimes eight poles. Dynamos with more than two poles are frequently called 'Multipolar' machines.

Fig. 206 illustrates a four-pole Victoria dynamo, four being the number most frequently employed. Each cast-iron pole-piece which partly embraces the armature has connected to it two

cylindrical wrought-iron cores, the outer ends of these cores being bolted to the cast-iron standards forming the yokes.

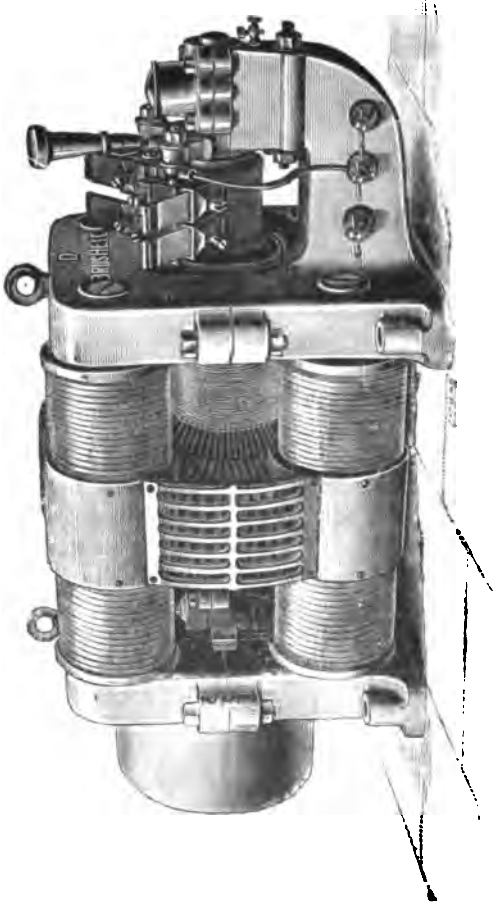


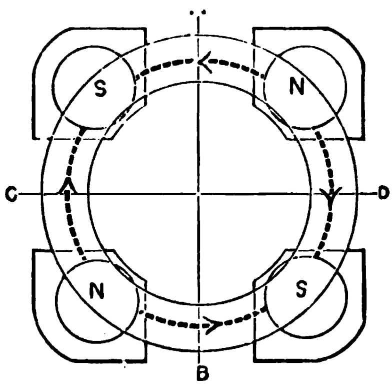
FIG. 2[illegible].

The two coils on each pair of cores are so wound that their similar poles are adjacent to the cast-iron pole-piece between them, thus developing a strong field from the pole-piece. These pole-

pieces are magnetised in this way alternately north and south, the arrangement of the entire field being that shown in fig. 207, where the direction of the lines of force through the armature core when it is at rest and the field undistorted is shown by the arrow-heads. The lines of force enter at the outer circumference, and also at both sides of the armature.

As the diameter of commutation is at right angles to the lines of force, and as in this multiple field there are two such diameters, A B and C D, two sets of brushes would appear to be necessary. This will be more apparent if we consider the inductive effects upon a single coil during a complete revolution. Supposing the coil to start from A, where its plane is at right angles to the lines of force, its upper portion will, in approaching the pole-piece, N, cut the lines of force from above, and in passing from N to D it will cut other lines, opposite in direction, from below, the result being that the induced current is in one direction only during the whole journey from A to D. Here the reversal takes place, for the coil, in approaching S, cuts these lines from above, and, passing S, cuts opposite lines from below, whence another continuous current is generated while the coil is travelling from D to B, where a second reversal takes place; and similarly with the other quadrants, the third reversal occurring at C, and the fourth at A. Or, viewing the matter from another standpoint, since the reversal of the current takes place at that moment when the maximum number of lines of force is projected through a coil, and as this maximum occurs at the point midway between each pair of pole-pieces (the field being still undistorted), it will be evident that the current must be reversed as the coil passes the points A, B, C, and D. Therefore, were the armature joined up in the

FIG. 207.



ordinary way, one pair of brushes must be placed on the diameter A B, and another on the diameter C D, to collect the current from all the coils.

To avoid the employment of four brushes a simple modification is made in the winding. As every pair of diametrically opposite coils is at every stage undergoing precisely the same inductive effect as the pair of coils situated at right angles to it, it follows that every two such pairs of coils can be permanently joined together in parallel, for they are at every moment developing equal E.M.F.'s. By this device only two brushes are necessary, one being set 90° ahead of the other.

The method by which this 'cross-connecting' is effected in the Victoria machine practically consists in joining together the diametrically opposite commutator bars, as illustrated in fig. 208.

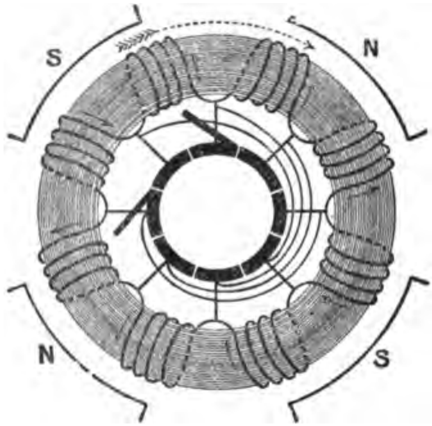
In this machine, as in every other, the reaction of the armature distorts the field and necessitates a forward lead being given to the brushes, which, however, are always separated by the same angle, viz. 90°. It must also be pointed out that there are always four paths open to the current through the armature, and that therefore the resistance from brush to brush is but one-sixteenth of what it would be were the whole of the coils joined in series. The low resistance thus obtained is an important feature in favour of multiple pole machines, for, in order to get with the ordinary ring or drum winding an equally low resistance, the conductor would have to be so massive that mechanical construction would be far less easy, and eddy currents would be generated in the conductor itself unless prevented by lamination.

In the case of a six-pole machine constructed on similar lines, either six brushes must be used, or, as is actually done, the commutator segments 120° apart, joined together in threes, two brushes being then employed with an angle of 60° between them.

In this class of machine, however, the adjacent pole-pieces, being of opposite polarity, must not approach each other too closely, otherwise an unduly large proportion of the lines of force will leak across the air-space instead of passing through the armature, and in any case the armature must be provided with sufficient iron to make the magnetic resistance low. Special care must also be taken with the lamination of the armature core. It will be

remembered that the eddy currents induced in a rotating core, as in any other moving conductor, are at right angles to the lines of force of the field, and also to the direction in which the conductor is moving. In the case of the ordinary simple-field machine, the lamination of the armature presents little difficulty, as the lines of force enter it from the outside circumference only. But the pole-piece *embraces* a flat-ring armature, and the lines of force enter at the sides as well as at the circumference, and it is therefore necessary to laminate the core in two directions, so as to avoid currents being induced either radially or in a direction parallel to the shaft.

FIG. 208.



For this reason an unusually large proportion of the space inside the coils of a flat ring armature is occupied by insulating material instead of iron.

Referring again to fig. 207, it will be seen that the direction of the lines of force through the armature is, as it rotates, frequently reversed, and that the number of reversals per revolution would be increased by increasing the number of poles. Such changes in magnetisation, if too rapid, would heat the core considerably on account of the hysteresis, and impair the efficiency of the machine, and this is one reason why more than six poles are rarely employed.

Fig. 209 is a sectional side-elevation, showing the construction of the Victoria dynamo, fig. 210 being an end elevation, half in section, of the same machine.

The core is built up by winding iron tape, 0·012 in. thick and about half an inch wide (with thin paper insulation), round a stiff wrought-iron foundation ring, which is of the same width as the completed core, and is slotted on both edges at four equidistant

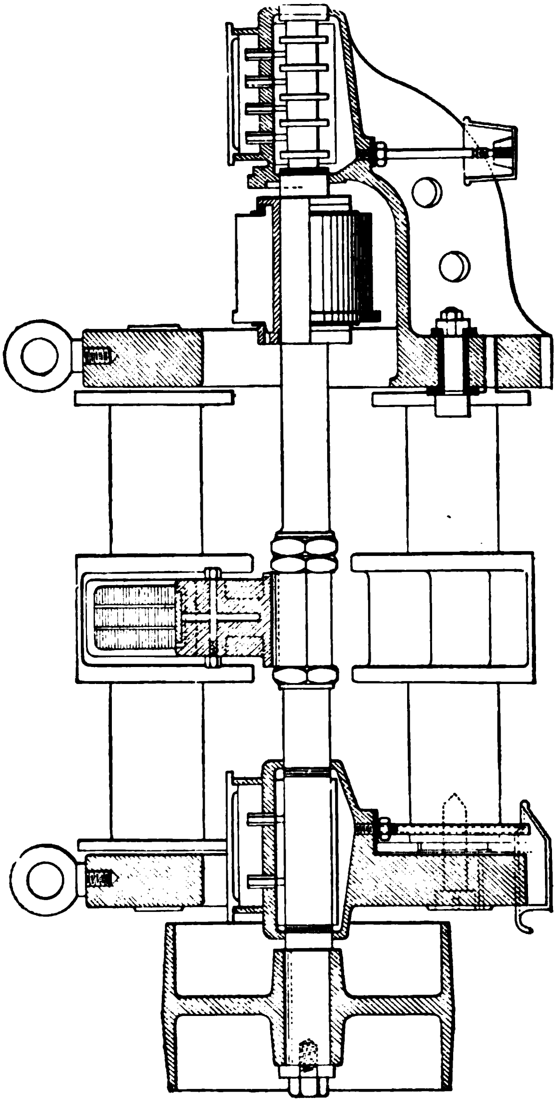
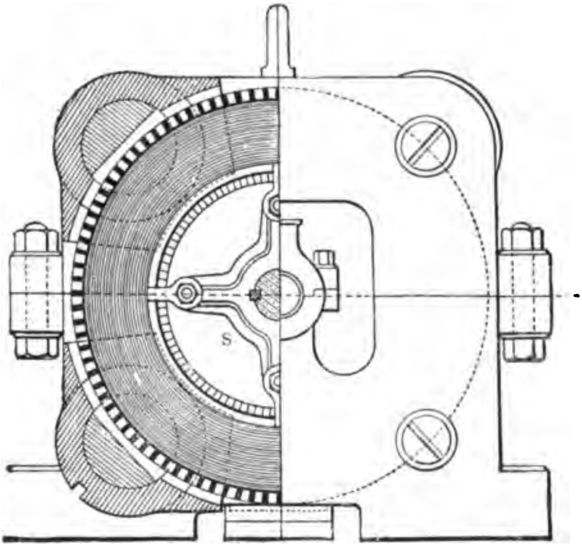


FIG. 209.

places. The four-armed gun-metal spider S (fig. 210) is made in two halves, held tightly together by hexagonal nuts screwing on to the shaft, to which also the hub is keyed. A bolt likewise passes through each of the arms, and when this divided spider is thus rigidly held in position, a little projection from the outer extremity of each arm fits tightly into one slot of the wrought iron foundation ring, and also extends a short distance into the core, a few of the inner layers being slotted for the purpose.

FIG. 210.



The section of the core is rectangular, and its radial depth is considerably less in proportion than that of the early flat ring armatures. Comparatively few of those lines of force which enter at the outer circumference penetrate through the whole depth of the core, and consequently the lamination near the foundation ring need not be carried to a very great extent to prevent the flow of currents in a direction parallel to the shaft. The strips are, for this reason, narrower and more numerous towards the outer circumference than near the inside.

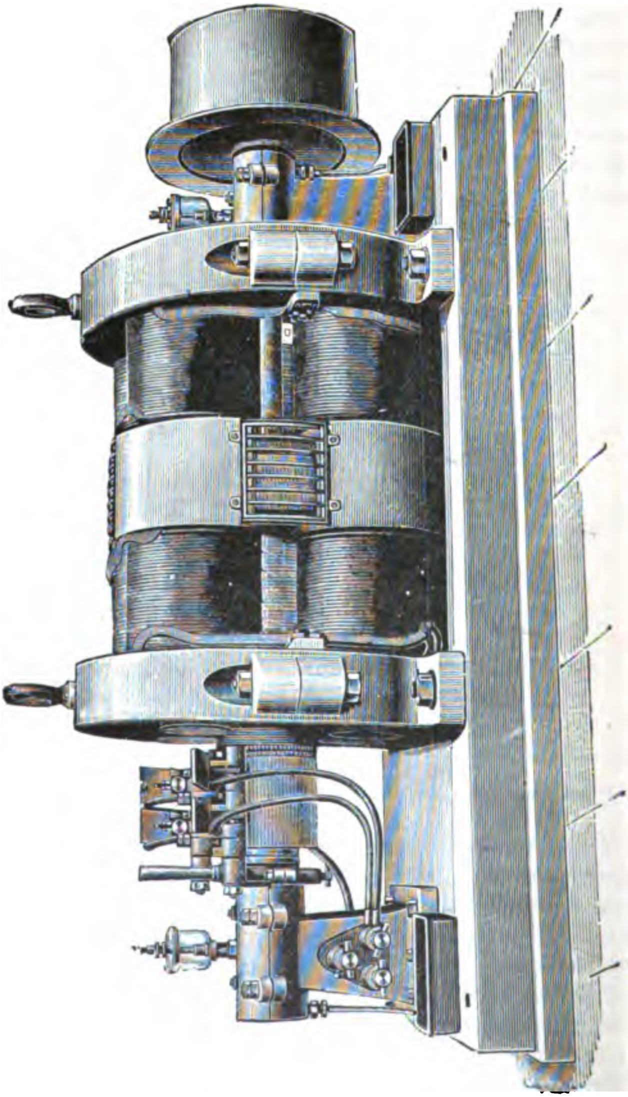


FIG. 211

The armature conductor is rectangular in section, insulated with tape, and is wound in one continuous spiral round the core, the connections from the commutator bars being soldered on at the proper points on the inside of the ring.

The armatures of the smaller machines are, however, wound with ordinary circular wire, cotton-covered, and well varnished.

Each of the vertical standards forming the yokes is cast in two pieces, which are bolted together, so that the upper portion of each, with the two upper field-magnets, can be removed to afford access to the armature. This arrangement is shown in the figures, from which it will further be seen that the upper part of the bearings can also be detached, thus enabling the armature to be easily lifted out of its position, when necessary, for examination or repair.

As in all other machines, it is necessary for the space between the field-magnet and the armature to be as small as possible, and since the pole-pieces extend over the sides of the latter, it is clear that there must be no end play, or shifting of the shaft lengthways; this is effectually prevented by the long-grooved bearing shown to the right in fig. 209.

The machine illustrated is intended to be driven at 1,000 revolutions per minute, and is then capable of developing 15,000 watts in the external circuit, at a terminal potential difference of 110 volts

The 'Battersea' dynamo (fig. 211) is another multipolar flat ring machine and is worthy of special notice. As has been remarked, such machines, while slightly less efficient than other forms, present in some respects fewer difficulties in construction, and the Battersea dynamo is, from a mechanical point of view, as well as electrically, an exceptionally good specimen of its class. Taken as a whole, however, a machine of this type is more expensive to construct than an ordinary two-pole dynamo of equal output, and for this reason it is dropping into disuse.

Fig. 212 gives a longitudinal section through one of these machines, a side elevation being shown in fig. 213. It is a four-pole machine, having an output of 12,000 watts.

The foundation of the armature core is the rim of a strong gun-metal wheel, which has four radial arms. The hub of the

wheel bears on one side against a collar on the steel shaft, as shown to the right in fig. 212; it is held tightly in position on the other side by a steel nut which screws on to the shaft. The core itself consists of soft iron wire rectangular in cross-section, and insulated with cotton. It is wound round the foundation-ring under high tension, the core thus built up being very strong and rigid.

We have referred to the necessity for lamination in two directions; and the smallness of the wire, and the efficiency of its insulation, practically eliminate eddy currents, while the thinness of the insulation and the tightness of the winding reduce the waste of space to the lowest possible limit.

The armature conductor, which is a copper strip, is wound over this core (embracing also the rim of the supporting wheel) in a single layer; the strip is rectangular in section, its dimensions being calculated so as to just occupy the allotted space round the circumference, and thus the distance between the pole-faces and the core is made a minimum. By the device of cross-connecting, the current is collected from a single pair of brushes, placed 90° apart. The method of connecting diametrically opposite pairs of coils in parallel is unique. On the shaft between the armature and commutator is fixed a wooden sleeve, over which a number of flat copper rings are slipped. These rings are carefully insulated, and each has two lugs projecting at opposite extremities of a diameter: a radial saw cut is made in each lug, just large enough for a copper conductor strip to be pressed in and soldered. The rings are so arranged that their lugs form a spiral round the shaft, and those connecting strips which lead from diametrically opposite coils of the armature to the commutator are soldered to the lugs of the same ring. In this way diametrically opposite bars of the commutator are joined together; one such connection is shown at the ring nearest the commutator in fig. 212.

The circular cast iron end frames forming the yokes to the field-magnets are in two halves bolted together, the lower half being also bolted to the bed-plate, as shown in the illustrations. These yoke-pieces are very massive, and, as the surfaces of contact between them and the wrought-iron cores are large and close-fitting, the magnetic resistance is low and a large proportion of the lines of force is led into the armature.

The whole armature conductor offers but little resistance, and as, by the cross-connecting, this is reduced to one-sixteenth of the resistance which would be offered were all the coils joined in series, but little power is absorbed in the armature, and the machine, which is shunt-wound, is self-regulating through a considerable range.

The commutator consists of eighty copper bars, with mica insulation, fixed, as shown in the drawing, by a gun-metal nut and washer, over a gun metal sleeve.

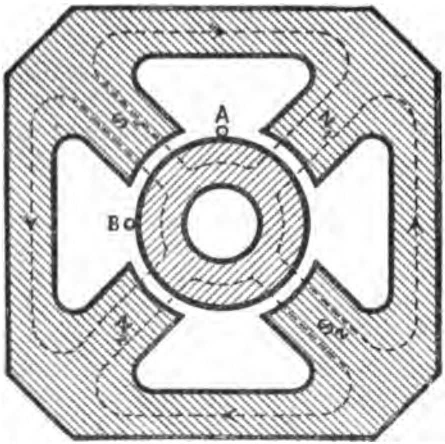
In smaller machines, circular copper wire, instead of rectangular strip, is employed for the conductor, and the magnetic resistance of the core is even further reduced by covering the iron wire with silk instead of cotton, the former occupying much less space than the latter.

Multipolar machines with drum armatures are now being somewhat extensively employed for large sizes, more especially in cases where the maximum current developed by the machine is very heavy. If a simple two pole field-magnet be employed, considerable difficulty arises with very heavy armature currents on account of the serious reactions on the field proper, the magnitude of these reactions being approximately proportional to the number of active conductors on the armature and to the strength of the current flowing therein. Among other things, the great distortion of the field at maximum load involves a considerable lead being given to the brushes, and a comparatively slight variation in the armature current necessitates a readjustment of the brushes to prevent sparking. The difficulty can, of course, be overcome, even with a simple field, but it is found to be less expensive for machines above a certain size to employ a field magnet with four or more poles, the magnitude of the reactions which have to be dealt with being approximately inversely proportional to the number of field-magnet poles when the armature conditions remain constant.

Fig. 214 illustrates the arrangement of the field-magnets and armature of such a four-pole machine. The field-magnet coils are usually wound on the straight limbs which project inwards from the outer framework, and each pole-face covers somewhat less than a quarter of the armature surface, without overlapping

or embracing the sides of the armature, as in the case of the two multipolar machines just described. The poles are alternately north and south, and the general direction of the lines of force is indicated in the diagram. It is evident that the armature conductors at opposite extremities of a diameter, which are passing under similar poles, must have induced in them a current in the same direction; for example, if the direction of rotation were right-handed, two conductors, passing respectively under S_1 and S_2, would have induced in them currents flowing upwards through the paper. If, therefore, an armature section were wound in the ordinary way—that is to say, if two diametrically opposite conductors formed one section of the armature and were joined to two adjacent commutator bars—no current would be obtained, the E.M.F. induced in one conductor neutralising that in the other, and this neutralisation would occur at every part of the field.

FIG. 214.



We may, in fact, select any one active conductor at any stage (except that in which commutation occurs), and we shall find that the conductor diametrically opposite it has a current induced in it in the same direction—that is to say, in any pair of diametrically opposite conductors the currents will flow either towards or away from the commutator end of the armature. Now these pairs of conductors may be so connected that they feed the external circuit either in series or in parallel; the former arrangement is adopted when the electro-motive force is required to be comparatively high with a correspondingly low current strength, and the latter when a heavy current with correspondingly low E.M.F. is desired.

If the series connection is adopted two sets of brushes only are required, set at an angle of 90° apart, the current having two paths open to it through the armature from brush to brush, as in an ordinary drum armature. The minimum number of active conductors joined in series thus becomes four per section, the current through any one section passing, say, from front to back along the first active conductor, returning by one situated 90° further on, then passing from front to back by a conductor yet 90° further ahead, and finally returning by one still further round by 90°.

When the parallel arrangement is followed the minimum number of active conductors per section is two, situated 90° apart, and, unless a method of cross connection similar to that described for the Mordey & Battersea flat ring armatures be adopted, four sets of brushes are necessary, these sets being 90° apart, and the diametrically opposite pairs positive and negative respectively. In most cases, as the current to be collected is heavy, the four sets of brushes are employed, opposite sets being directly joined together externally.

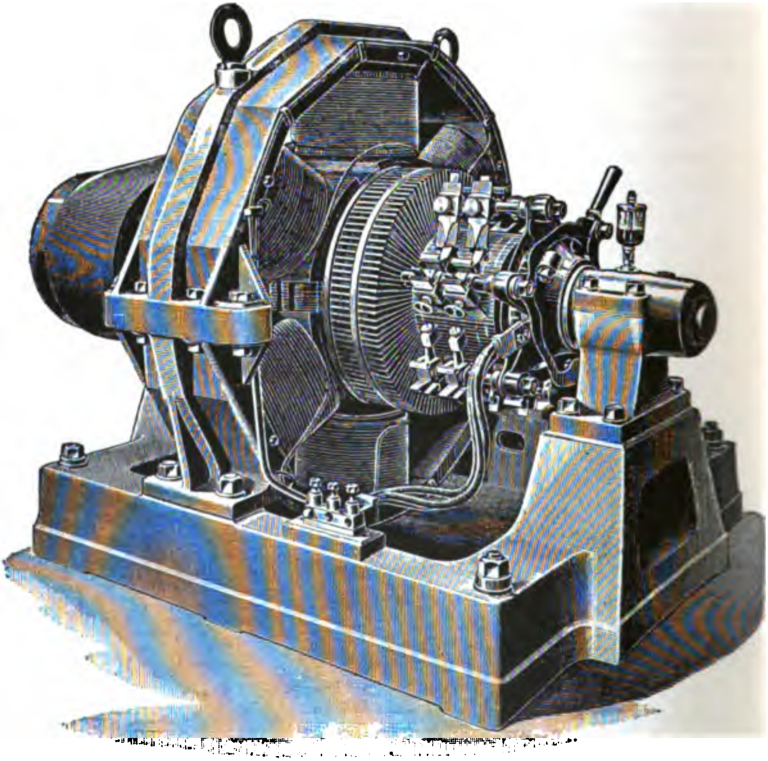
In fig. 214 A and B represent two active conductors placed 90° apart, and in the case of an armature with parallel connections these two conductors would be joined together by a cross-connector at the back, while their ends in front would be joined to adjacent bars on the commutator. It will be seen that the coil or section of which they form the essential part embraces practically the whole of the lines of force entering or leaving any one field-magnet pole while they are in a position similar to that shown in the figure. These conductors are most active when (allowing for a slight distortion of the field) they have each just passed the middle point of their respective pole-pieces, and least active when 90° from this point; so that the commutation takes place in this latter position, which is that indicated in the figure. In fact, it may be taken as a general rule for any type of machine that the reversal of current in, and therefore the commutation of, any one armature section always occurs at the moment when that section is embracing the maximum number of lines of force.

Ring armatures are sometimes employed with field-magnets of this type, but the conditions are similar to those obtaining with

the Mordey and Battersea flat disc armatures, except that, since the lines of force enter at the outer surface of the armature only, and not at the sides, the core need only be laminated in one direction.

Some important multipolar machines with drum armatures have been designed by Mr. Kapp, and constructed by Messrs.

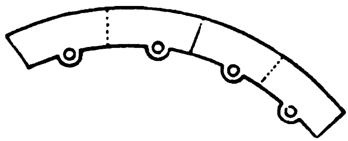
FIG. 215.



Johnson and Phillips for Central Station work. One of these machines with six poles is illustrated in fig. 215. The field-magnet cores and yoke are of cast-iron, the outer frame forming the yoke, and the cylindrical inwardly projecting portions constituting the cores upon which the field-coils are wound. The faces of the

cores are provided with rectangular extensions, as shown, to cover a larger portion of the armature surface. The cores and yoke are in two castings bolted together, and the upper portion, with its three coils, can readily be removed for the inspection or replacement of the armature by simply removing the four bolts on either side and disconnecting the coil connections. The core of the armature is 24 inches in diameter and 12 inches in length; and the thickness of the core (that is to say, the distance from the inner to the outer circumference of the core-plates) is 3 inches only. The mass of iron thus afforded for the core might at first sight appear to be small for such a large machine, but it must be remembered that in a multipolar dynamo the lines of force do not all enter at one point and leave at another, but all those entering from any one pole leave the core at the two adjacent poles, which are of opposite polarity. It would be a somewhat expensive matter to construct such a core of discs, each stamped or cut out of one sheet of iron, and the cores are built up with sheet-iron segments, each with two holes on the inner side, which are threaded over iron bolts. Two adjacent segments butt end to end as shown in fig. 216, while the middle of a segment in the next row comes opposite the joint. The large space inside the core allows unusually good facilities for the ventilation of the armature.

FIG. 216.



The six poles are alternately north and south, and consequently any three active conductors on the armature separated by a space equal to 120° will, at any moment, be undergoing precisely the same inductive action. If the parallel system of winding be adopted, as is the case with the machine under notice, there will thus be six paths open to the current, and six sets of brushes are here employed. The rocker is a compound one, the two parts being insulated from each other, but connected respectively to the positive and negative terminals of the machine. One part of this compound rocker carries the three positive sets of brushes, which are placed 120° apart, and the other part carries the three negative sets, which are placed alternately with the former sets.

The ends of the active conductors are connected by cross-connectors similar to those employed in the two-pole Kapp machine previously described, but in this case the connectors extend only 60° round the end of the drum instead of 180°, as does that illustrated in fig. 192.

There are 224 active conductors round the armature, the armature resistance being but ·0015 ohm, and all the field-magnet coils are joined in series with each other, forming a shunt to the external circuit. When driven at 450 revolutions per minute the potential difference at the brushes is 50 volts, the maximum current being 1,000 amperes. If the armature of this machine were series-wound, in the manner indicated above, with two sets of brushes, three times as many active conductors would be placed in series, giving a potential difference of 150 volts, the maximum current then being 330 amperes.

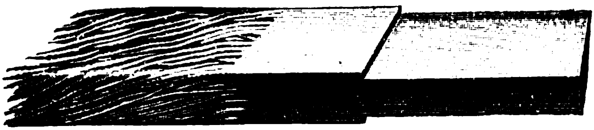
In concluding this chapter, we may with advantage make a few further remarks concerning the losses which reduce the efficiency of a dynamo. Omitting the power absorbed in overcoming the conductor resistance, which can easily be calculated, the losses may be classified under three general heads: (*a*) mechanical friction; (*b*) eddies in conductor; (*c*) losses in armature core. The friction occurs principally at the bearings—for the commutator brushes should exert only just sufficient pressure to insure reliable contact—and the loss due to this cause increases regularly with the speed at which the machine is driven. In order to make the friction at the bearings as low as possible, care should be taken that the armature is perfectly balanced magnetically as well as mechanically, while the bearings themselves should be well designed and well made. A good lubricant should be employed, and should the accidental entrance of grit or dirt or any other cause give rise to undue heating, the bearings should be carefully cleaned at the first opportunity, and, if necessary, scraped.

When the conductor is massive, as in the case of a bar armature, the eddy currents in it may be sufficiently important to absorb a considerable amount of power, and, as we have seen, such conductors are frequently laminated, or sometimes braided wire is employed, to prevent the circulation of the currents. The laminated armature bar most frequently employed is that made by Messrs. W. T.

Glover & Co., and shown in fig. 217. It consists of a number of bare copper wires twisted together and then compressed into rectangular bars. As the electro-motive force tending to set up the eddy currents is exceedingly feeble, very slight insulation suffices ; the thin film of oxide with which copper becomes coated upon exposure to the air is sufficient, provided the pressure applied in compressing the wires has not been great enough for the wires to break through this film and make metallic contact ; but, as a further precaution, the wires are usually coated with oil. To facilitate connection between the ends of the bar and the cross-connectors and the connection from the commutator segments, a solid end is sweated on to each extremity of the stranded bar.

Lamination of the iron core, if properly performed, also reduces to a minimum the eddies in the iron ; but there is another source of loss which arises when lines of force passing

FIG. 217.



through iron are rapidly reversed or altered in direction, due to the phenomenon known as hysteresis. This loss appears to be the result of a kind of internal friction between the molecules of the iron when they change their position, as we believe they do, under the influence of the magnetising force. At any rate, it is not possible to project lines of force through iron, or alter their position, without a small amount of work being performed independently of that resulting in eddies.

This question has already been referred to at the end of Chapter VII., and it will be remembered that the energy lost by hysteresis per cubic centimetre of iron depends upon the value of the maximum induction B and also upon the coercive force of the iron employed. Thus, for one particular specimen of iron, when B = 18,000, Dr. Hopkinson estimated that 13,000 ergs were expended in twice completely reversing the magnetisation, or in performing the complete cycle of operations as indicated by the

curve in fig. 122. If iron of this description were employed for an armature core having a mass of, say, 1,000 cubic centimetres, and if the 18,000 × 1,000 lines of force were twice reversed, say 50 times per second, the energy lost by hysteresis per second would be 13,000 × 1,000 × 50 = 650,000,000 ergs. Since a loss of 10,000,000 ergs per second is equivalent to one watt, this would represent a loss of $\frac{650}{10} = 65$ watts.

As, however, any vibration to which the iron may be subjected assists in the changing in position of the particles under the influence of the magnetising force, and as the armature of a dynamo machine when running experiences considerable vibration, the losses due to hysteresis are in practice somewhat less than those calculated from experiments made with the specimen free from vibration. The reduction in the hysteresis effect by vibration is, however, less when the induction is high, as in the case of an armature core, and in any case the small advantage accruing from this vibration does not in any way diminish the importance of selecting iron of low coercive force.

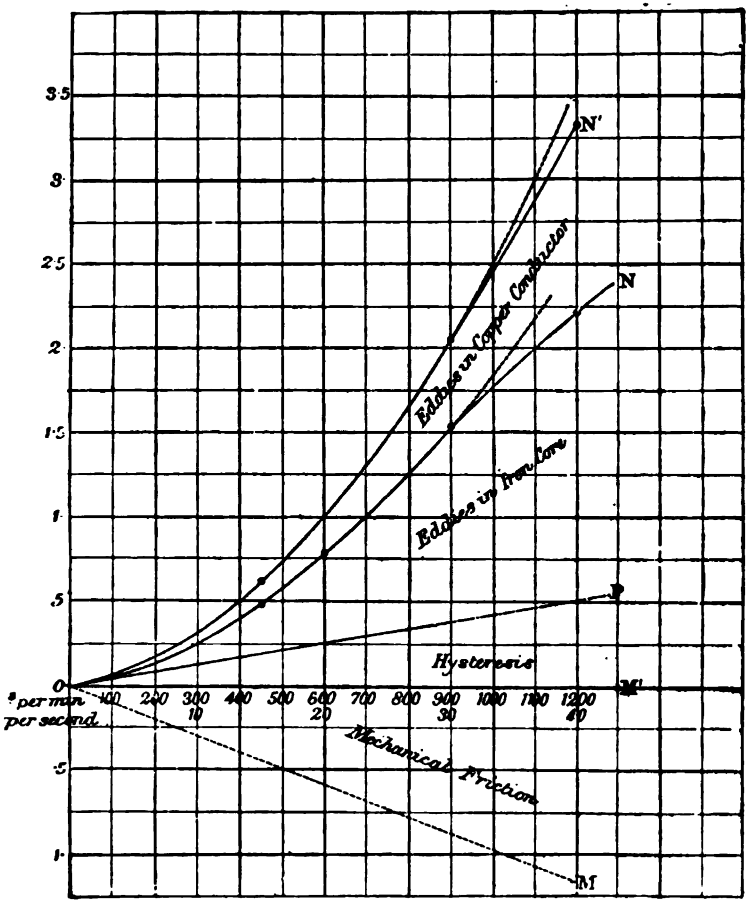
It is a most important matter to separate, if possible, the various sources of loss in any dynamo, in order to ascertain what parts of the machine, if any, need altering in design. This separation has been effected practically by Mr. W. M. Mordey, who plotted his results in the curves shown in fig. 218. The machine experimented with was a direct-current Victoria dynamo, with an output of 18,000 watts, the speed being varied up to 1,200 revolutions per minute. The armature core consisted of iron strip, 0·012 inch thick, with thin paper insulation, the cross-section of the iron in the core being 12 square inches, and the magnetic induction through it 12,300 C.G.S. lines per square centimetre.

The dynamo had four poles, and, therefore, the lines of force through the core were twice reversed, or carried through a complete cycle, twice in every revolution.

The machine was first driven with the field-magnets disconnected, the iron having been deprived of its magnetism by a rapidly alternating current; and the power then absorbed, measured by a transmission dynamometer, gave, at various speeds, the value of the power spent in overcoming the mechanical friction. Since

the iron in the magnet cores always retains some magnetism, a small amount of power would be absorbed in the production of

FIG. 218.



weak eddy currents, were this residual magnetism not carefully eliminated.

In fig. 218, O M, representing the friction loss, is plotted below

the base line, so that the relation between the other curves can be more clearly seen.

In order to obtain the total losses in the iron core, the field was then separately excited to its normal strength by means of a secondary battery, and the armature core, without the copper conductor, driven at various speeds, the power absorbed in driving being measured as before.

This power is the sum of that absorbed by friction, eddies in the core, and hysteresis; and by subtracting the friction the two latter quantities remain, and are plotted at O N in the figure.

On winding the armature and repeating the experiments, the curve O N′ was obtained, and the difference between the ordinates O N′ and O N represents the loss due to eddies in the copper conductor.

But the important problem is to find a means of separating the hysteresis and eddy current losses in the core; this was accomplished, and the line O P represents the loss due to the former.

The method of separation is simple, and depends on the fact that while the loss due to the eddies varies, with a given number of lines of force, as the square of the speed, the loss from hysteresis is proportional to the speed simply.

Therefore, if two speeds are taken, such that one is double the other—for instance, 450 and 900 (see the figure)—the height of the hysteresis ordinate, from O M′ to O P, at the higher speed, will be twice the height of the ordinate at the lower speed; while the height of the eddy-current ordinate from O P to O N will be four times as great at the higher as at the lower speed.

After a few trials, the two points between O M′ and O N which satisfy these conditions can be found; and the line O P, drawn through these points, separates the loss caused by hysteresis from that due to eddy currents.

The curves O N, O N′ show the actual loss experimentally observed, but a dotted branch line is added to each, which indicates the curve which would be obtained if the rate of loss of power had been maintained with the increase of speed up to 1,200 revolutions. It will be observed that the actual loss agrees with the calculated loss until a speed of 900 is reached, from which

point, for some reason not clearly understood, it falls below the calculated value.

The vertical sides of the squares represent 0·25 of a horse-power, while the horizontal sides represent 100 revolutions per minute, or 3·3 complete magnetic cycles per second; and it will be observed that although the lamination of the core has been carried to a high degree, yet the loss due to eddies is considerable, and cannot by any means be ignored. One object of these experiments was to demonstrate that, however well laminated, the iron cores in the armature of an alternating-current dynamo are the seat of a considerable amount of loss, and this has undoubtedly been proved to be the case. The departure from the calculated rate of loss at the higher speeds, as evidenced by the bending down of the curves, prevents, however, the method being directly applied to alternating machines, where the reversals are considerably more rapid than when the disturbing causes begin to manifest themselves. The method is, however, apparently reliable in the case of direct current machines running at a moderate speed, and it possesses the all important advantage that the tests are made under conditions similar to those which obtain in practice.

CHAPTER XI

DIRECT CURRENT DYNAMOS (OPEN COIL)

In the armatures of the direct-current machines hitherto described, all the coils are connected together, and the junction of each adjacent pair is joined to a bar of the commutator. But there is another method of constructing an armature, in which the coils are kept quite separate, each coil having in the simplest form a separate two-part commutator. The former are known as 'closed-coil,' and the latter as 'open-coil' armatures. Machines for developing very high electro-motive force are usually built with open-coil armatures, an E.M.F. of 2,000 volts being not uncommon; and such machines are frequently used for electric lighting in cases where the type of the lamps and their disposition are such as to require the transmission of a current of moderate strength through a comparatively high resistance. In a closed-coil armature the E.M.F. generated by every coil in any and every position, excepting at the moment when it is short-circuited by the brush, forms a part of the total E.M.F. of the machine and does its share towards urging the required current through the external circuit. On the contrary, in an open-coil armature the current is collected from a coil while it is in or near the position of greatest activity only, or while the E.M.F. induced in it is at or near its maximum, the coil being thrown out of circuit during the time that it passes through the period of least activity. At the beginning of this latter period another coil enters the best position, and commences to feed the circuit. The coils may be wound either on the ring or drum principle, and in the former case the two coils at

opposite extremities of a diameter are usually joined together in series and may be treated as one coil.

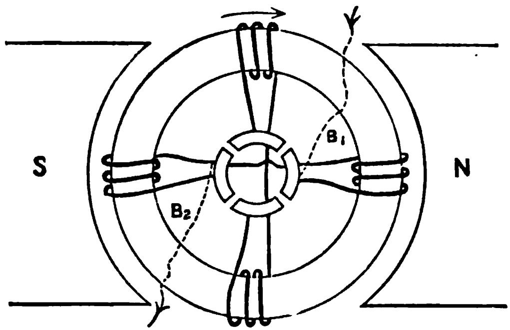
Many of the elementary principles examined in connection with the machines already described, hold equally well for those with open-coil armatures, and while it is unnecessary to again enter into a lengthy discussion of these matters, we may say, briefly, that the field will be distorted in the same manner, and that the position of maximum activity for any coil will be that in which its plane is parallel to the lines of force of this resultant field. To minimise the distortion, and to obtain a high E.M.F. for a given speed of rotation, the field-magnets must in this case also develop as strong a field as possible.

The high E.M.F. developed requires, however, even greater precautions as regards insulation than are taken with ordinary closed-coil machines, and this point must be carefully kept in view in designing and selecting the materials for the insulation both of the armature and of the field-magnet coils. In closed-coil machines the maximum electro-motive force developed is as a rule comparatively low; and the potential difference between adjacent coils and commutator bars being only a fraction of the total potential difference at the brushes, the difficulties in the way of efficient insulation, even in exceptional cases when the machine is designed to produce a comparatively high electro-motive force, are not so great as might appear at first sight. But while in a closed-coil machine the number of active conductors joined in series is never more than half the total number, in an open-coil machine the proportion is not only greater, being usually about two-thirds, but consists of those in the most active positions; and further the total number of convolutions in the armature is much greater; so that open-coil machines are more suited to the development of high electro-motive forces. It is evident, however, that if the coils are cut out of circuit while they are fairly 'active,' there must be some means of dealing with the inevitable sparking; it must either be minimised by some arrangement of the commutator, or its destructive action prevented.

The fundamental principle of all open-coil dynamos is illustrated in fig. 219. Two pairs of coils are shown, wound round an iron ring, at right angles to each other. The commutator has

four parts, or, strictly speaking, there are two two-part commutators, and each of these two-part commutators is connected to the ends of its particular pair of coils. Two flat springs, B_1 and B_2, act the part of brushes. In considering the action of the machine we will, in order to simplify matters, assume that the field is undistorted. Since we desire to take the current from the coils while they are at their maximum activity, the brushes must be placed along a diameter parallel to the lines of force, a position exactly opposite to that of the brushes on a closed coil machine. The two horizontal coils by this arrangement deliver their current to the external circuit while the vertical ones, being comparatively idle, are entirely disconnected. The activity of the horizontal pair

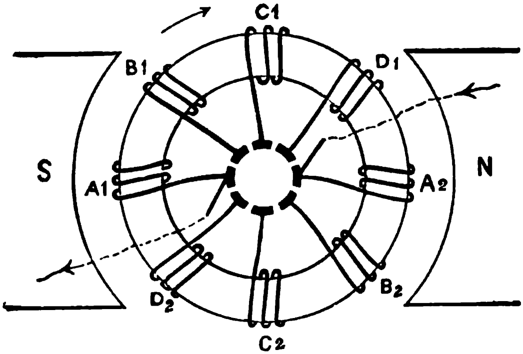
FIG. 219.



decreases as they move from this position, and when the armature has revolved through another 45° they are thrown out and the other coils begin to feed the circuit. Each pair is thus alternately joined up to and disconnected from the brushes for a period equal to a quarter of a revolution; and an ammeter placed in the external circuit would indicate a current, always flowing in one direction, but fluctuating considerably in strength Greater steadiness — that is to say, a nearer approach to constancy - can be obtained by increasing the number of coils, although it is not possible to get a current so nearly constant as that which a good closed-coil dynamo can generate. In fig. 220 the number of coils is increased to eight, that is, four pairs. The two coils at opposite extremities

of a diameter, A_1 A_2, for instance, are joined together to form a pair as before; but to avoid a complicated diagram this connection is not shown, and the distortion of the field is again ignored. Each pair has its two-part commutator, the segments of which are (including the insulating space between the adjacent segments) one-eighth of the circumference of a circle, or 45° in length, and therefore each pair of coils is connected to the brushes for one-eighth of a revolution only. If the strength of the field, the number of convolutions per coil, and the speed of rotation were the same as in the case just considered, the maximum electromotive force developed would be the same; but as the minimum

FIG. 220.



does not now fall so low during the time that the coils are connected to the brushes, the result is a more uniform current in the external circuit.

It will probably occur to the student that the coils D_1 D_2 and B_1 B_2, although far less active than A_1 A_2, are yet in a position where they can generate a considerable E.M.F. and that they might with advantage be allowed to assist. But they must not be joined up *in parallel* with A_1 A_2, since their E.M.F. is so much less. Were they to be so joined up we should get a result similar to that obtained when a Grove cell and a Daniell cell are connected in parallel, in which case the Grove cell would urge a backward current through the Daniell because it has a higher E.M.F., and the external circuit would therefore get actually less current than

if the latter cell were removed altogether. But if the two are joined up *in series* then the external circuit gets the whole current resulting from the sum of their two E.M.F.'s. In the same way, if the effect of the coils in positions of less activity is to be utilised, they must be joined up in series and not in parallel with those developing the higher E.M.F. We will explain how such an arrangement is effected in one of the best known open-coil machines, viz. the 'Brush' dynamo. Now in the case of a set of four pairs of coils rotating in a uniform field, as in fig. 220, it is clear that at one time, only one pair of coils can be in the best, and only one pair in the worst, position for generating a current. On the other hand, it is possible for two pairs to be equally active in an intermediate position, and this will happen when they make an angle of 45° with the lines of force, that is, in the position occupied by B_1 B_2, and D_1 D_2. In the Brush dynamo, when the armature thus consists of eight coils in four pairs, two pairs of brushes are employed, one collecting the current from the pair of coils in the best position only, A_1 A_2, while the other joins up the two pairs of coils which are at the moment in the intermediate position, B_1 B_2, D_1 D_2, *in parallel*, and collects the current from them. The two pairs of brushes are joined in series, and thus the E.M.F. of the intermediate pairs of coils is *added* to that of the pair of coils in the best position, only one pair, as C_1 C_2, being thrown idle at a time. As the intermediate coils are placed in parallel their resulting E.M.F. is the same as that of one of them, the resistance being,

FIG. 221.

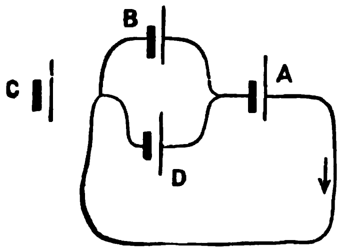
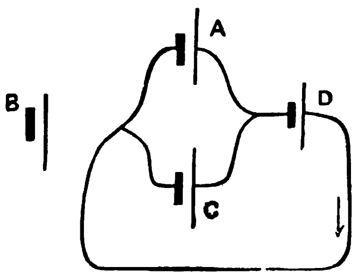


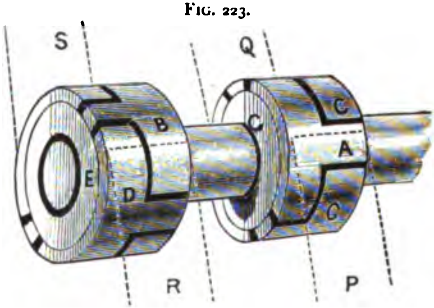
FIG. 222.



however, halved. In order to make this quite clear we may represent a pair of coils as we do a primary cell, and then show the arrangement, as in fig. 221, where A represents the most active, and C the least active pair of coils, B and D being those in the intermediate stage. When the armature has turned through another 45°, the B coils are idle, the D are at the maximum activity, and the A and C in parallel, as shown in fig. 222.

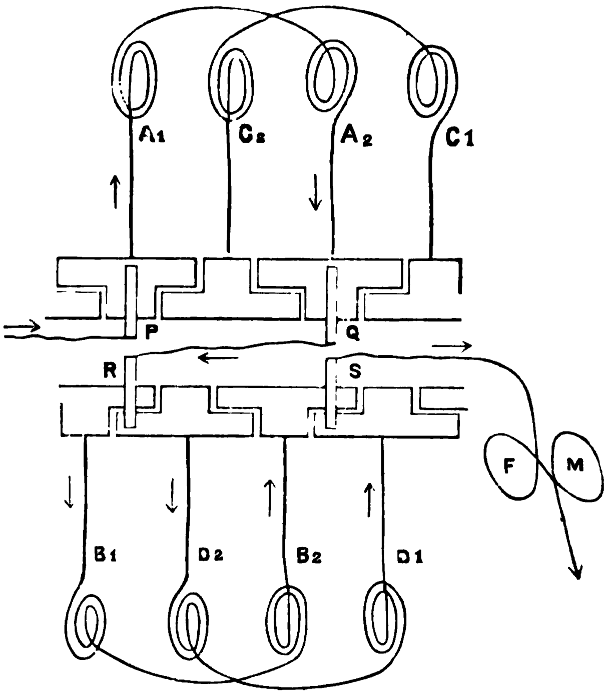
The commutator, by means of which these changes are effected, is illustrated in fig. 223. It is divided into two portions, each complete in itself, and consisting of four thick T-shaped pieces of brass separated from the shaft by rings of insulating material, E G; the T-shaped sections being insulated from each other by air-spaces. The brushes, P Q R S, are formed of flat copper strips, and, as shown by the dotted lines, are sufficiently wide to cover the whole width of the commutator rings. The ends of a pair of coils are joined to diametrically opposite segments or sections as indicated in the figure, the lettering in this illustration corresponding to that in fig. 220. One of the commutator rings is fixed on the shaft 45° in advance of the other, the consequence of which is that when, on one ring, each of the brushes is resting on one section only, as at A, then each brush on the other ring is in contact with two sections, as at B, D. The student will perceive that in the case illustrated the sections of the left-hand commutator ring have joined to them the two pairs of coils which are for the moment in the intermediate position, and therefore require to be placed in parallel; while the right-hand ring has joined to it the pair (A) which is in the best position and also the pair which, being inactive, is entirely disconnected from the brushes and the external circuit.

FIG. 223.



In fig. 224 the two double commutators are developed or spread out, side by side, to make the matter clearer, the lettering of the coils being the same as in fig. 220. The path of the current is easily traced. It passes round the pair of coils, A_1 A_2, the brushes P and Q (by which it enters and leaves) each resting

FIG. 224.



on one section only, because those coils are in the best position. The current then passes direct to the brush R (on the left-hand part of the commutator), which, resting on two sections, affords a path through B_1 B_2 and D_2 D_1, in parallel. The brush S, by which it finally leaves, is connected to one end of the field-magnet coils, F M; the coils C_1 C_2 are disconnected. Such is the action

which takes place in a Brush dynamo having four pairs of coils in its armature.

The actual machine is depicted in figs. 225 and 226, the latter of which is an end elevation from the commutator end. The cores of the field-magnets are almost oblong in section, and are securely bolted to cast-iron uprights which form the yokes. These two horizontal horse-shoe field-magnets are placed with their similar poles opposite each other, and project a powerful field round the armature, half of the lines of force passing through the core above, and the other half below the shaft, somewhat similarly to the case of a two-pole closed-coil machine with a ring armature. There is an unusually large

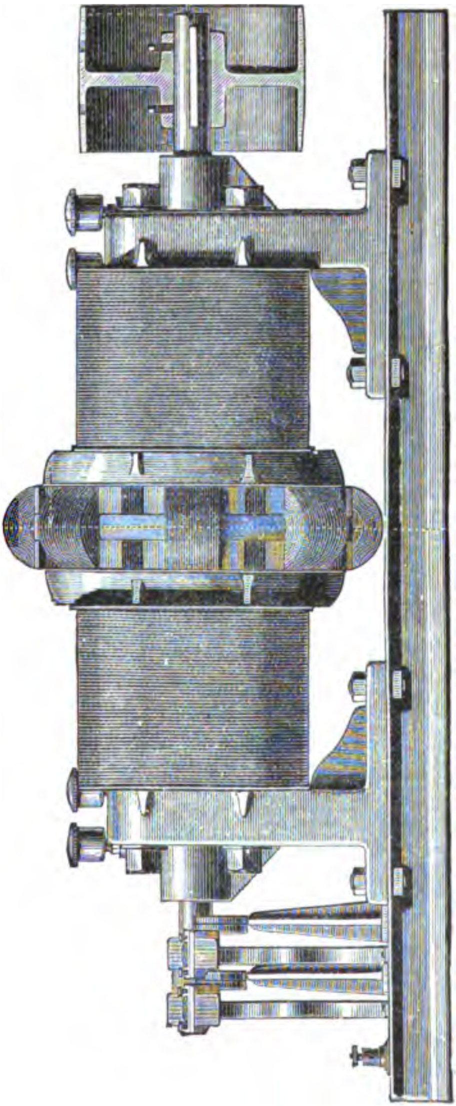
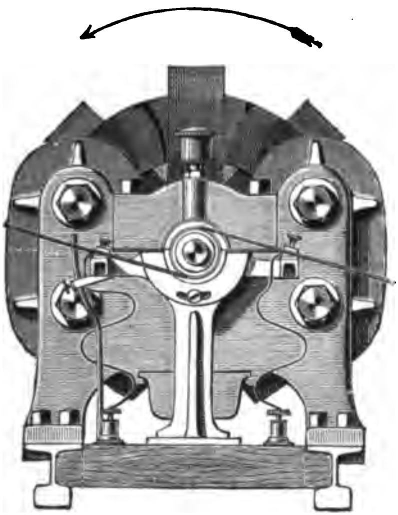


FIG. 225.

quantity of iron in the armature core, and careful lamination is needed to reduce the loss of energy due to eddy currents.

The method of building up this core is illustrated in fig. 227. A thin soft iron ribbon is wound in a continuous spiral round an iron foundation ring A. Between the successive convolutions of the ribbon, and held by them as the process of construction is carried out, are placed H-shaped iron stampings, S, of the same thickness as the ribbon. The connecting portion of these stampings lies wholly within the turns of the ribbon, the ends then projecting and forming spaces, as at B, within which the coils are wound. The stampings are all of one size, so that adjacent sets in the inner portion of the ring are nearer to each other than in the outer portion, while the sides of the channels in which the wire is wound are parallel. The whole is rigidly fixed together by means of insulated bolts, *b*, passed radially through the H-pieces, the spiral ribbon, and the foundation ring, A′, as shown in the sectional view. The stampings and ribbon are, however, proportionally much thinner than they are shown in the figure, and consequently the number of turns is much more numerous. The loss occasioned by eddy currents is thus reduced to a fairly low value.

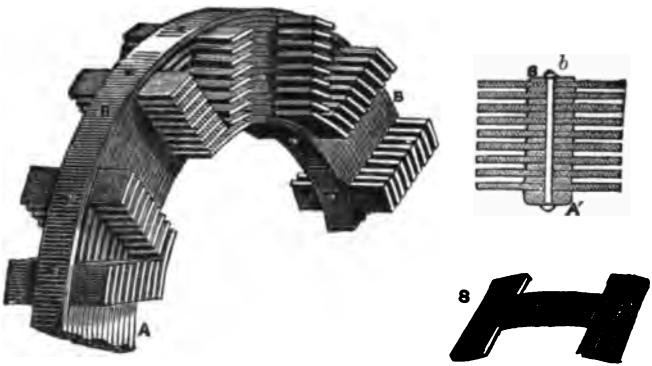
FIG. 226.



The armature coils are insulated from the core by sheets of canvas and paper, treated freely with shellac varnish, the layers of wire being insulated by cotton-cloth. The ends of each pair of coils are carried along the shaft to their proper sections of the commutator.

The field-magnet coils are also carefully insulated from their cores by vulcanised fibre and varnished paper, the different layers being separated, as in the case of the armature, by cotton-cloth. These coils are joined up in series with each other and with the armature, and as the current generated by the machine fluctuates more or less, there is a tendency for eddy currents to be induced in their unlaminated cores. This tendency is overcome by the simple device of interposing between the coils and the iron a tube of thin sheet copper, in which the currents are induced instead of in the iron. These induced currents by their reaction upon the field-magnet coils tend to reduce the

FIG. 227.



fluctuations of the primary current, and the high self-induction of the field-magnets and armature also tends to prevent any sudden variation of current strength, so that the resulting current is always more regular than might be expected from a consideration of the manner in which it is collected.

The pole-pieces are extended so as to embrace an unusually large portion of the armature, and the opposite pole-pieces being similarly magnetised, the lines of force are not projected axially through the armature, but entering the core on both sides, by the projections formed by the H-pieces, they tend to pass circumferentially round a portion of the core and leave it at another set of H-pieces, near the other poles. The lines of force are in this way

urged through and cut by the coils as they rotate. The maximum induction in the armature core is considerably greater and that in the field-magnet cores somewhat less than obtains in ordinary low-pressure closed-coil dynamos.

The diameter of greatest activity is approximately in a line with the upper horn of the right-hand pole-piece, and the lower horn of the left-hand pole-piece (fig. 226), as will be gathered from the position of the brushes, the direction of rotation being left-handed as viewed from the commutator end. As the machine is regulated to give a constant current, the reaction of the armature on the field, and therefore also the lead of the brushes, varies only slightly under ordinary changes in the load. The current taken from the armature has practically the same value under all circumstances; but, as will be seen presently, the regulation is effected by shunting part of the current from the field-magnet coils when a lower electro-motive force is required, and consequently as the field varies somewhat in strength as the load changes, the re-action of the armature on the field is not absolutely constant. The small amount of adjustment of the brushes thus necessitated is usually effected by hand, but occasionally it is performed automatically, the rocker carrying the brushes being shifted into the correct position by an electro-magnet.

When the brushes are in the correct position it is not possible to altogether avoid sparking, and for this reason the commutator wears out much more quickly than does that of a closed coil machine. It is, however, so constructed that any one or more of the segments can be readily, and at a comparatively small expense, replaced, and the sparking is thus rendered a not very serious matter.

The machine illustrated is designed to supply 55 arc-lamps in series, with a current of 10 amperes, the speed being 800 revolutions per minute and the maximum E.M.F. about 2,750 volts. The figures are both drawn to scale, the principal dimensions being: length of bed-plate 7 ft. 10 in., width 2 ft. 5 in., height of highest point 3 ft. 1½ in., outside diameter of armature 2 ft. 9 in. The diameter of the shaft is 2¾ in., its centre being 1 ft. 9½ in. above the floor line.

Although most Brush dynamos are employed on arc-lighting

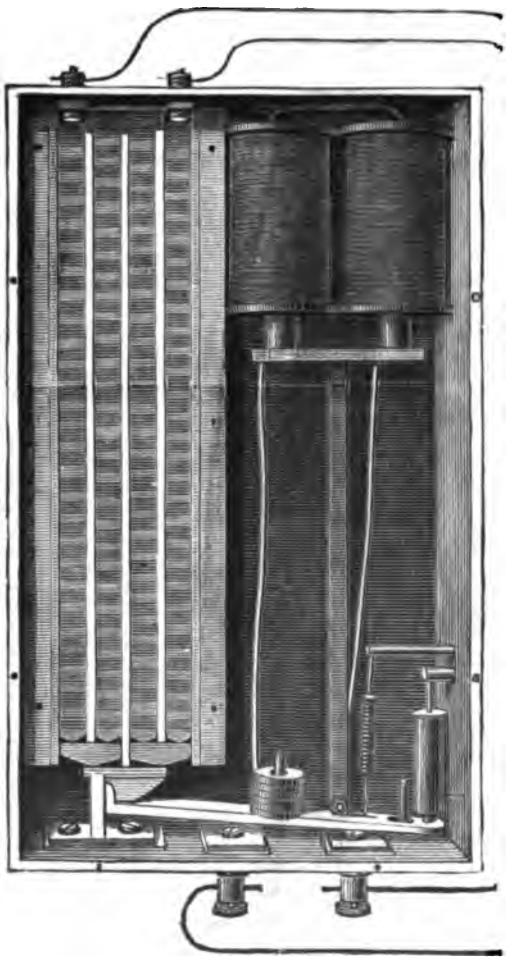
circuits where a current of 10 amperes is required, a different current strength is sometimes desired, and a machine such as that under consideration can, without much trouble, be altered to give a current of 20 amperes with half the electro-motive force developed when 10 amperes are being obtained. To effect this change it is necessary in the first place to connect every diametrically opposite pair of coils in parallel instead of in series, and secondly to join the four field-magnet coils in two sets of two in parallel instead of all four being in series. It will be observed that after this change has been made, every armature coil and every field-magnet coil carries a current of 10 amperes as before; the strength of the field remains unaltered, but the number of armature convolutions joined in series is halved, and therefore the resulting electro-motive force is also halved.

The brush-holders are connected to terminals on the bed-plate by means of flexible copper strips, and, as shown in fig. 226, each pair is carried by a rocker which can be turned round the shaft, its range being, however, limited by the length of the slot in the semicircular collar directly under the shaft. The left-hand end of the rocker is furnished with a small projection riding over a curved guiding-fork, the position on the fork being fixed by means of a set screw.

Although this machine is capable of driving as many as 55 arc-lamps joined in series as its maximum load, the number of lamps actually switched in circuit may vary considerably from time to time; but the act of switching out a lamp by short-circuiting it, reduces the external resistance, and the machine being series wound, the current strength is then proportionally increased. It is nevertheless essential that under all conditions the same current strength—viz. 10 amperes—should be maintained: hence some regulating device becomes necessary. The regulator devised for this purpose by Mr. Brush is illustrated in fig. 228. It consists of four vertical columns of thin retort-carbon plates separated by vertical slate partitions. These columns are joined in series between the two terminal screws at the top, connection being made between the two inner columns at the top, and between the outer pairs of columns at the bottom, by means of carbon slabs. Wires are led from the two top terminals to the ends

of the field-magnet coils, across which these carbon columns form a shunt, whose resistance can be varied by altering the pressure upon the plates. This pressure is automatically increased when the current rises above its normal value, and the resistance of the shunt being thus reduced, a larger proportion of the current is abstracted from the field-magnets, and the strength of the field and current kept at their proper value. The method of accomplishing this is illustrated in the figure.

FIG. 228.



The two solenoids are joined up in the main circuit by wires connected to the terminals shown at the bottom of the case. Projecting partly into the coils are two soft iron cores, rigidly fixed to a common yoke-piece, the centre of which carries a brass rod attached at its lower extremity to one end of a horizontal lever,

whose fulcrum is a knife-edge at its extreme left end. When by the switching out of lamps, or from any other cause, the main current passing through the solenoids increases, the cores are sucked upwards with greater force, and the block on which the four columns rest is raised through a short distance by the lever, thus compressing the carbon plates and reducing the shunt resistance, with the result that the current in the field-magnets is proportionally reduced. On the other hand, should the main current fall below 10 amperes the soft iron cores drop slightly, allowing the horizontal lever to fall also, with the result that the pressure on the carbon plates is reduced, and the shunt resistance increased; a stronger current then flows through the field-magnet coils, and the field becomes sufficiently powerful to develop an E.M.F., which can generate a current of 10 amperes through the total resistance in circuit. A dash-pot is attached to the free end of the lever to prevent sudden or jerky movements, the normal adjustment being obtained by means of a spiral spring and a few small weights slipped over a vertical pin.

Several modifications of this regulator are in use, but they all act similarly in shunting current from the field-magnet coils to such an extent that the field becomes of the requisite strength to enable an E.M.F. to be generated which shall be competent to give a current of the standard strength through the total resistance of the circuit at the moment. In one form greater sensitiveness is obtained by employing a relay to control the electro-magnet which actuates the compressing lever, and a thin wire resistance is added to shunt the carbon columns in order to prevent the arc which would form when they break contact with the blocks at the top of the column, which sometimes happens when the machine is fully loaded and no current is required to be shunted from the field-magnet coils.

In another type two carbon plates are hung vertically from a lever, their lower ends dipping into water. The lever is raised and lowered by an electro-magnet controlled by a relay; the carbon plates rise and fall with the lever, and are thus immersed to a less or greater extent. Each carbon plate is connected to one end of the field-magnet coils, and when the plates fall they present a

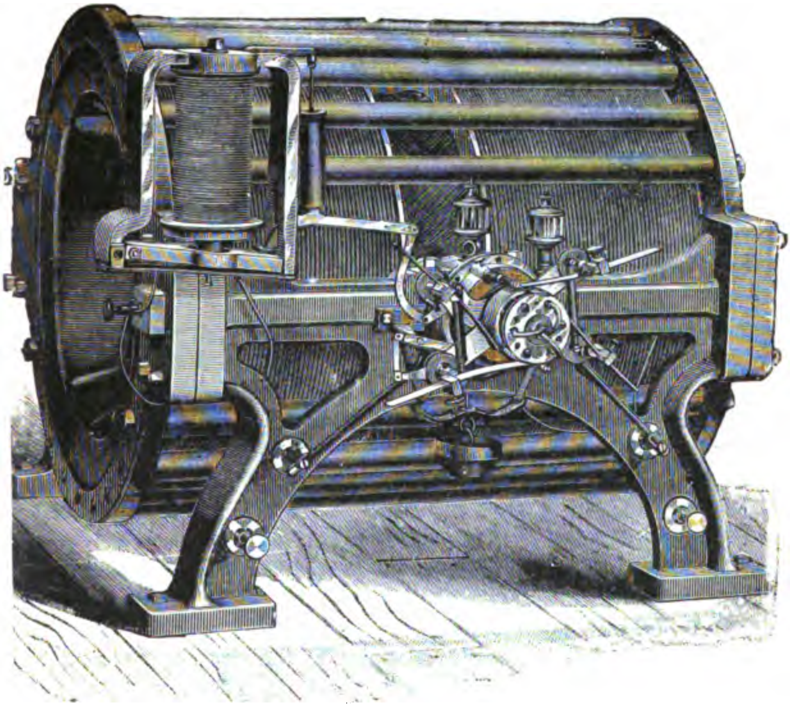
greater surface to the liquid, and the shunt resistance is thus reduced, and *vice versa*.

As might be expected, the efficiency of the Brush machine, and indeed that of any open coil dynamo, does not compare favourably with that of a good low-pressure closed coil dynamo. The commercial efficiency of modern Brush machines, that is to say, the ratio of the electrical power available for use in the external circuit to the power applied mechanically, may be taken at from 60 to 70 per cent. In order to effect any great improvement on these figures it would probably be necessary to so alter the design of the machine that its distinct peculiarities which render it so well fitted for its particular work would be lost, and this loss would not be compensated for by the gain in efficiency. At present the machine will stand far more rough usage, and far greater stresses due to sudden changes in the load, than will an ordinary highly efficient closed coil dynamo (in fact, no machine of the latter class could use up so much energy internally and survive); its high self-induction is more beneficial than baneful, and with its regulator a current constant enough for all practical purposes may be relied upon. Further, if the efficiencies of the two types be compared by taking the power actually given to two machines (one closed coil and one open coil), and dividing by the number of lamps maintained in either case, the difference will be found to be comparatively small, especially if some of the lamps are at a distance from the machines, because in the case of arc-lamps driven in parallel from a low-pressure dynamo, various other sources of loss are introduced. This question will be again referred to after arc-lamps have been discussed.

The only other form of open-coil dynamo in general use is the Thomson-Houston, of which a view is shown in fig. 229. It is a machine by itself, having many peculiar features, altogether different from those of any other with which we have dealt. There are two field-magnets placed horizontally, with their opposite poles facing each other. There is comparatively little iron in the cores, each of which consists of a cast-iron tube flanged at both ends, and provided at the armature end with a spherical cavity to form the pole-piece. The shape of the armature itself is that of a slightly flattened sphere, somewhat like an orange, and it revolves

between and partly within the cup-shaped pole-pieces. The wire on each field-magnet core is wound in the space between the flanges, the outer flanges of the two cores being deeper than the inner ones, and affording, thereby, means for a number of wrought-iron bars to be bolted through them. These bolts add materially to the mechanical strength of the machine, protect the coils from

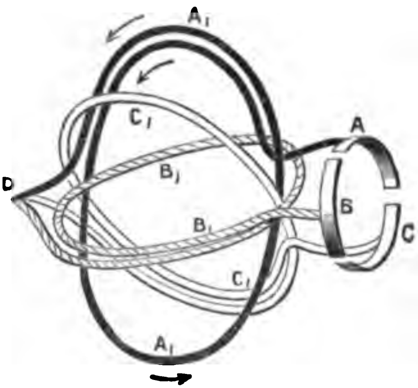
FIG. 229.



injury, and form the yoke of the field-magnets. The machine, which, on account of the small quantity of iron employed in its construction, has but little weight, is supported by comparatively light but strong standards, which are bolted to lateral projections from the flanges of the field-magnet cores. These standards also carry the armature bearings.

The manner in which the armature core is built up is also interesting. Upon the shaft are keyed two stout cast-iron discs, each provided on its inner face and near its periphery with an annular groove. About a dozen wrought-iron ribs are sprung into the pair of grooves, so as to bridge the space between the discs and form a circular framework, round which a number of layers of varnished soft iron wire is wound. This forms the complete core, into which, however, a number of wooden pegs are fixed, to guide the winding of the coils and to hold the wire in position. Before the coils are wound on, the core is insulated by layers of paper fastened by means of gum-lac.

FIG. 230.



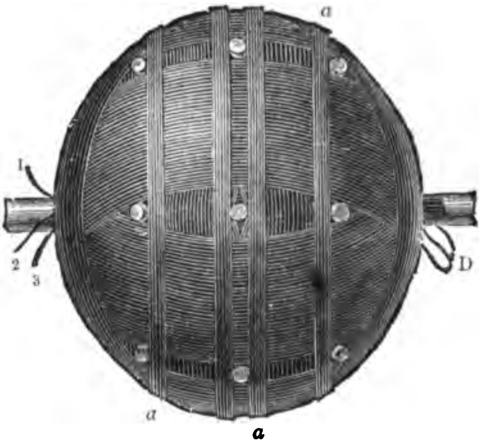
The armature consists of only three coils, and fig. 230 illustrates, in the simplest manner, the way in which they are wound. The inner ends of the three coils are soldered together, as at D, and the junction carefully insulated. Starting from this junction, each coil is wound over the core, with an angle of 120° between the middle portions of the coils, the three free ends being joined, one to each segment, A, B, or C, of the three-part commutator.

A view of the completed armature is shown in fig. 231, and it will be observed that the overlapping of the coils near the shaft causes the form to become almost spherical. The junction of the three coil-wires is shown at D, the free ends, 1, 2, 3, being brought out, on the other side of the armature. The coils, when finished are bound round at four places with binding wires, *a a*.

It is essential that every armature should be truly balanced, not only mechanically, but also electrically—that is to say, all the coils should be of the same area and equidistant from the core and pole-pieces, so that the inductive effect on each is precisely

the same, and they should be all of the same length and of the same resistance. It is evident, therefore, that it would be inexpedient to wind the three coils in this spherical armature completely one over the other. But the length and the average distance from the core of all the coils is made equal by a very simple method of winding. Starting at the junction D, half of one coil is wound; then, 120° further round the core, half of the second coil is wound; yet another 120°, and the *whole* of the third coil is wound. The second half of the second coil is then wound over its first portion, and, finally, the remainder of the first coil is wound over the corresponding first portion.

FIG. 231.

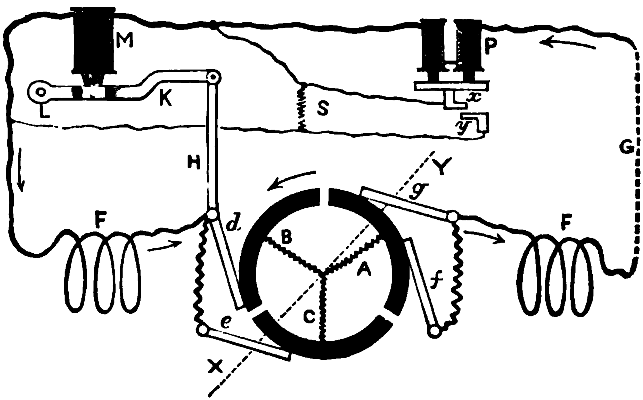


When the armature is rotated, currents, alternating in direction, are induced in each of the coils; the reversal, as usual, taking place in each case when the plane of the coil is at right angles to the lines in the resultant field. The reaction of the armature, of course, distorts the field somewhat, and shifts it round through a certain angle in the direction of rotation, as shown by the dotted line X Y in the lower part of fig. 232. In this figure, each radial line, A, B, C, represents one of the armature coils, the three coils being united at the centre and each one joined to its respective commutator segment. The current is collected along the diameter of maximum activity, X Y, by two pairs of brushes, *d*, *e*, and *f*, *g*, each pair being electrically connected. The two brushes forming a pair are normally so placed that one presses on the commutator at a distance equal to 60° in front of the other. The consequence of this arrangement is that the most active coil is joined up in series

with the remaining two less active coils, which are joined together in parallel. In the case shown in fig. 232, the coil A is approaching the best position; while B and C are in the intermediate stage, and are therefore joined up in parallel. The resulting E.M.F. is, consequently, that due to the mean E.M.F. of B and C, added to the separate E.M.F. of A. As the armature rotates, B approaches the best position, and its commutator segment alone is then in contact with the brushes *d*, *e*, while C and A, which are brought to the intermediate positions, are joined in parallel. These changes are continually repeated as the coils pass through the different portions of the field.

As in the case of the Brush dynamo, this machine being series wound and used on a circuit of high resistance for driving a large

FIG. 232.



number of arc-lamps joined in series, the switching out of any of the lamps tends to cause an increase in the current strength, while, conversely, the switching in of lamps causes a diminution. Hence, in order to keep the current at a nearly constant strength, some regulating device is necessary. The method adopted consists in simply altering the position on the commutator of the two brushes forming each pair. It will be observed, from the commutator in fig. 232, that, the brushes being 60° apart, no coil is thrown out of circuit at any part of the revolution, and this is what

we may call the normal state of affairs. When, however, the current falls in strength, each pair of brushes is closed up automatically, so that all the coils are, in turn, disconnected for a moment when they are passing the neutral position, and when they are, therefore, nearly idle. The E.M.F. of the two coils in parallel is the mean of their individual E.M.F.'s, and is, obviously, lowered by a comparatively idle coil, so that, at the moment when the idle coil is thrown out, the E.M.F. resulting from the other of the two coils in question is greater than it would be were they both in parallel. If this closing up of the brushes were to take place, then, when the armature is in the position shown in the figure, the comparatively inactive coil B would be disconnected, and A and C joined to the external circuit in series. The maximum E.M.F. would be developed when each pair of brushes is so closed up as to form practically one brush, in which case the least active coil would be always out of circuit and the other two joined up in series. From this point any opening of the brushes puts two of the coils in parallel for a greater or less interval of time, and reduces the resulting E.M.F.; therefore when the current becomes abnormally strong, the brushes are opened until the E.M.F., and, consequently also, the current, are reduced to the normal value. The motion given to the brush-holders by the regulator is such that the following brush of each pair travels three times as fast as the leading brush.

The brushes *d*, *e*, *f*, *g*, are mounted on a double lever, having a scissors-like movement about a common centre. The end of the lever carrying the brushes *d* and *f* is connected by the bar H to the armature K, under the electro-magnet M. This armature is hinged at L, and when the current in the main circuit becomes excessive, K is attracted, *d* and *f* are drawn back over the commutator, while *e* and *g* are pushed forward by a simple combination of levers not shown in the figure. The electro-magnet M and the double solenoid P are both in the main circuit with the field-magnets F F and the lamps G; but normally M is short-circuited by wires whose circuit may be broken at *xy*. The contact *x* is attached to the yoke of the two cores of the solenoids, and the first effect of an increase in the current is to raise the cores, break the contact at *xy*, and so cause the whole

of the current to pass through M, which then attracts K and opens the brushes. A high-resistance carbon shunt is inserted at S to minimise the spark at *xy*. It will be noticed that the end of the core of M is shaped somewhat peculiarly and fits into a corresponding cavity in the armature; this shape is calculated to diminish the force of attraction uniformly as the armature recedes from the core. The regulating apparatus is shown in position in fig. 229. The small cylinder to the right of the electro-magnet is a dash-pot for steadying the movements of the lever.

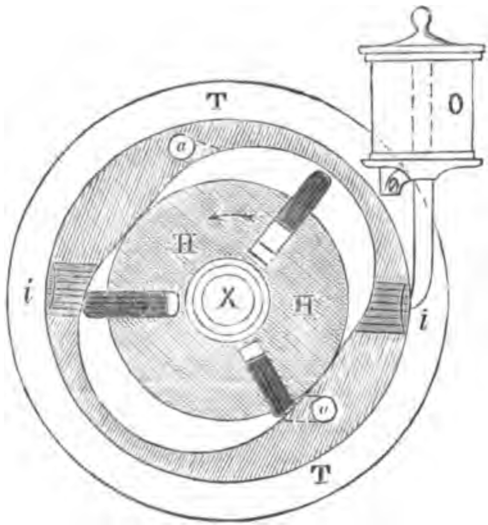
There is one other device pertaining to the Thomson-Houston machine to which a reference is necessary, and which is employed to suppress the excessive sparking caused by cutting out the coils when fairly active, and which would otherwise speedily destroy the commutator. The segments are separated by air-spaces, and just in front of each leading brush is placed a nozzle which delivers a strong blast of air at the moment that the brush breaks contact, and so prevents the passage of the spark. The automatic 'blower' by which these timely puffs are delivered is shown in section in fig. 233. A circular steel hub, H, is keyed on to the shaft, X, and revolves left-handedly in an elliptical chamber in the fixed box T T. Air enters this chamber through the apertures at *i i*, which are protected by wire-gauze coverings. The hub H is provided with three radial slots, in and out of which the rectangular ebonite slips can slide freely. As the shaft rotates these slips fly outwards by centrifugal force, and, pressing continually against the walls of the chamber, force the air in front of them, and out at the holes *a a*. To each of these holes is connected one of the two nozzles above referred to. The chamber is fixed to the framework of the machine in the necessary position for the maximum force of the blast to take place at the right moment. O is a vessel from which oil passes into the elliptical chamber through the aperture *i*.

The machine illustrated is designed to supply a current of about 9½ amperes to 34 arc-lamps in series. The armature is 2 feet in diameter, over all, and the resistance of the field-magnets and of the armature is in each case 10½ ohms.

In addition to the dynamos which have been described in

this and the preceding chapters, there are many others to which the scope of this work has not permitted us to refer, although some of them are well worthy of study. We believe, however, that quite enough has been said to give the student a good insight into the science of dynamo-building as it is now practised. Where we have given sectional views or working drawings, they have for the most part been specially prepared for this work, and we have selected for such illustration those machines which we

FIG. 233.



consider are best suited to show the manner in which theoretical principles are practically applied.

A comparison of these chapters with works of a similar character published a few years previously will show that the modern trend in dynamo design is towards simplification and uniformity of detail. As an example of the latter, we may cite the construction of commutators, in which the materials now employed are nearly always exactly alike, while in the manner of building up the parts so as to prevent the sections flying out, there is very little real difference to be found. This similarity is what might, perhaps,

have been anticipated; for, if the vast number of experiments which have been performed by the various manufacturers to determine which is the best appliance to perform a given kind of work, have been equally exhaustive and accurate, an almost identical result should have been arrived at. Thus, no metal has been found superior to hard-drawn copper for the bars of a commutator, while for the extremely difficult task of satisfactorily insulating these bars in the case of a closed-coil commutator, nothing has been discovered which approaches mica; indeed, were this mineral not available, it is probable that some alteration would have had to be effected in the general design.

Great things were at one time expected of asbestos for insulating purposes, but it proved to be a good absorbent of oil and was charred by the sparking, while the adhesion of metallic particles abraded from the bars and brushes, soon developed a greater or less amount of short-circuiting with its concomitant evils. A somewhat similar result attended the use of simple air-spaces for insulating the bars, for the metallic dust or scrapings accumulated sooner or later at the bottom of the spaces, which, being numerous, were necessarily narrow. Occasionally a special form is given to a commutator; for instance, that of the small exciter shown in fig. 136 is built against the end of the armature, the individual bars being disposed radially. The object here is to reduce the length of the machine. A special commutator is also employed with the machine illustrated in fig. 237, the object of which is explained in the description.

Again, the lamination of the core of an ordinary ring or of a drum armature is a matter upon which little doubt now exists, for it is as certain as it well can be that the magnetic resistance should be kept as low as practicable, a result only to be arrived at by retaining metallic continuity in the direction of the lines of force; on the other hand, the lamination must be carried far enough to sufficiently reduce the eddy currents, while every effort is made to make the quantity of iron as great as possible by using extremely thin insulation. Nothing better, therefore, can be devised than a core of thin iron plates of high permeability, separated by the thinnest possible layer of insulating material, the only doubtful point being the thickness of the plates. The thinner the plates are made the

more is the loss of power by eddy currents reduced, but the proportion of space occupied by insulation and the expense of construction are correspondingly increased. While it is not possible to state definitely what the exact thickness of the core plates should be for any given case, it can be safely said that it is economical to reduce the hysteresis loss as far as possible, by adopting the only known course of experimentally selecting for the core plates, iron of low coercive force.

With regard to closed-coil armatures, it is probable that the ring form will in the future be even less frequently employed than it is now, the drum type having been proved to possess so many important advantages. On account of the ease with which efficient ventilation can be secured, the ring armature will probably survive for small machines. The drum armature with a simple field seems best adapted for machines of moderate size; while for machines of large output with heavy armature currents, the drum armature with a multipolar field (four or six poles) is increasing in favour, partly on account of the fact that the difficulties due to the reaction of the armature on the field are less formidable than with a simple field. The multipolar machines with flat-disc armatures are dropping out of use, as it is found that the advantages which they afford cannot be fully developed without comparatively expensive construction. Thus, again, we see that the result of experience is to reduce the number of types to one or two distinctive ones, whereas a few years ago almost every individual machine might be said to be of a class peculiar to itself.

Indeed, the principal difference now apparent in the construction of dynamos is in the form and arrangement of the field-magnets, and this matter is, for machines of a given output, now almost entirely determined by the relative expense in construction, Every designer attains the desired end by adopting the form and material which, with the tools and appliances at his disposal, he considers will be the least expensive.

In special cases the question of weight may be all-important, demanding the use of wrought-iron where otherwise cast-iron or a combination of wrought and cast iron would be the more economical.

The theoretical form of field-magnet core, circular in section (so as to require the minimum amount of wire), and made of soft iron without molecular discontinuity, is too expensive and inconvenient to be rigidly followed, especially in large machines. Where the part of the core actually embraced by the wire is cylindrical and of wrought-iron, it is usually fitted with cast-iron pole-pieces and yoke, of correspondingly greater sectional area. Mild steel, which can now be obtained with a permeability almost equal to that of the best wrought-iron, has been used to a certain extent. It has the advantage that it can be cast to any desired shape as readily as cast-iron, but it cannot yet compete with wrought-iron in price when the latter material is used to the best advantage, that is to say, when the design of the machine is such as to enable the desired result to be obtained with the minimum quantity of iron and the minimum amount of machine work on it.

The position of the armature with respect to the yoke of the field-magnet in a two-pole machine is usually determined solely by the manner in which the machine is to be driven. If it is to be driven direct by a high-speed engine, then its armature spindle must be in line with and coupled to the crank-shaft of the engine; and since practically all high-speed engines are of the vertical type, with the crank-shaft below the cylinders, the armature spindle is required to be low down, and then the machine is preferably made with its armature below the field-magnet coils and yoke. This construction admits of great compactness being obtained, and also steadiness in running, since the position of the centre of gravity of the armature is low. Should the field-magnets be multipolar, the armature shaft can be brought to the most convenient distance from the floor level by cutting out a space in the engine-room floor to take the lower portion of the field-magnets. When the machine is to be driven by a belt or ropes, most makers prefer to adopt, for two-pole machines, the design in which the armature is placed above the field-magnets. The purpose for which direct-current dynamos are most frequently designed is to light a number of incandescent lamps joined up in parallel circuit. It is necessary to maintain a constant potential difference at the terminals of these lamps, say of 110 volts, and

consequently the machine employed should be shunt-wound, with a very low armature resistance ; or, if the number of lamps is likely to be subject to considerable variation, the machine may be compound-wound. For the important work of 'charging' secondary batteries, a simple shunt-wound machine is, for reasons explained in Chapter XIV., the most suitable.

Many dynamos are now employed for the deposition of metals, electroplating, &c., and for this purpose they are in some cases required to furnish very heavy currents at an exceptionally low potential difference. They are frequently series-wound, and it is necessary that the internal resistance should be extremely low, otherwise considerable power would be wasted by the passage of the current, which sometimes exceeds 1,000 amperes. To obtain this low resistance a drum armature may be constructed with very massive bars for the active conductors, the field-magnet coils consisting of a few convolutions of massive copper band. An electromotive force of from six to eight volts is usually ample, and this, notwithstanding that there are but comparatively few active conductors round the armature, can be obtained without the necessity for driving at a high speed. But it is not an easy matter to secure these massive bars, and consequently many machines are made with a number of fairly thick wires joined up in parallel to form one conductor. In order to reduce as far as possible the loss of energy at the commutator it is essential that the brushes should be large, and the amount of contact surface considerable. Machines of such exceptionally low E.M.F. are, however, falling into disuse, the more recent practice being to join the depositing tanks in series, and to employ a machine giving a correspondingly higher E.M.F.

A large machine, somewhat similar in appearance to that depicted in fig. 193, has been constructed for electro-deposition work ; it develops the comparatively high E.M.F. of 50 volts, and can yield 1,000 amperes at a speed of 350 revolutions.

Multipolar machines, as has already been indicated, afford a means of easily securing mechanical strength with extremely low resistance, the latter advantage resulting from the fact that there are four or more paths for the current through the armature. Further, if a method of internal cross-connection be not adopted,

a large number of brushes may readily be employed, thus obviating the difficulties sometimes incurred in collecting a very heavy current from a commutator.

For supplying current to a number of pieces of apparatus joined up in series, whether arc-lamps, low-resistance incandescent lamps, or motors, it is necessary to maintain a constant current under all conditions. The two open-coil machines described in this chapter, and the dynamo illustrated in fig. 205, are suitable for this class of work, the first-mentioned being the most extensively used for the purpose.

CHAPTER XII.

MOTORS AND THEIR APPLICATIONS

WE must now give some attention to the important class of dynamo-electric machines employed for the purpose of converting, at any desired point, energy supplied to the machine, in the form of electricity, into energy in the form of mechanical motion.

In its widest sense this conversion rests upon the fact that whenever any of the lines of force forming part of two separately generated magnetic fields traverse a common space, there is a decided action between the two sets of lines, the tendency being to so alter their paths that as many lines as possible shall coincide in direction. By bearing in mind this simple general rule, little difficulty should be experienced in predicting the results which will follow, even in complicated cases. This mutual action takes place independently of the means by which the fields are developed, whether by currents in two wires (straight or coiled, with or without cores), or by permanent magnets ; or, the one field by a current in a wire and the other by a magnet. In the effort to make the coincidence a maximum, both fields are distorted from the configuration which they would independently have retained, and this configuration is again assumed immediately they are removed from each other's influence. Consequently, when the lines of force pertaining to two fields approach each other, their mutual action sets up a stress, the effect of which is a tendency to impart such a motion to the material substances (whether a steel bar or a conducting wire) employed in generating the fields, as to make them take up positions in which the lines of force due to both fields coincide to the greatest possible extent. The stronger the fields, the greater is the force thus acting, and, if sufficiently strong, mechanical motion is imparted to that body which moves

the more freely. For instance, suppose one field to be a simple one developed between the two pole-pieces of a powerful field-magnet such as has been described, and the other field to be generated by a current in a circular loop of wire. If the loop is placed vertically with its edges towards the pole-pieces, that is, with its plane parallel to the lines of force of the field-magnet, then the lines of its own field will be projected at right angles to those of the other, and the field-magnet being too massive to move, the loop will, if freely suspended, immediately turn round through 90°, when the lines of force due to the field-magnet thread through it in the same direction as its own lines. If free to move in any direction, its ultimate position of rest will be in the densest portion of the field, where the number of lines passing through it, and coinciding in direction with its own lines, is a maximum. If the current through the loop is then reversed in direction, it will turn completely round until the lines of both fields again coincide.

We have thus a means of imparting mechanical motion to a material substance, in this case a loop of wire; and a continual rotatory motion can be maintained by reversing the current in the loop at the right moment, viz. just when its momentum has carried it a little beyond the point which, in the absence of this reversal, would be its position of rest. It remains to be seen how the principle is practically applied, on a scale such that the force with which the movable body is urged into a new position may amount to many horse-power.

Referring to the simple case of a closed-coil armature with a two-part commutator, as illustrated in fig. 151, it will be observed that if a current is sent through the two coils in parallel while in the position shown, no movement results when the direction of the current is such that the lines of force due to it coincide in direction with those of the fixed field. This is the position of rest for the armature, and if the current in it is reversed, it will make a complete revolution until the same coincidence again exists. Now the current can be supplied by brushes pressing on the commutator segments, and so placed that each segment slides into contact with a fresh brush directly the position of rest is arrived at. By this means the current will be reversed, and a continuous rotation kept up. With only two coils, the armature

might come to rest suddenly at a dead point, and would not start again from such a position ; but the number of coils can be increased with advantage until we have, practically, an armature similar to those used in generators. On a current being sent through such an armature, each coil strives to set itself with its plane at right angles to the field, in which position the coincidence of the two sets of lines is at a maximum. Immediately the coil arrives at this point, the current in it is reversed, causing it to exert a similar force in the same circular direction, during another half-revolution.

The armature may be of the ring, drum, or flat-disc type, and it fortunately happens that most of the principles underlying the design and construction of a good generating dynamo, hold equally well for a motor. The fixed field is usually supplied by powerful electro-magnets, as in the case of generators, these being excited by a current from the same source as that which supplies the armature. Many of the troubles which in dynamos are avoided or reduced by the employment of a fixed field sufficiently strong to overpower that developed by the armature, are also inherent in a motor, and may be avoided by the same device. But in a motor the question of weight is frequently of considerable importance. For instance, the machine may be employed for the purpose of propelling a vehicle, and in such cases the weight of the motor is added to that of the vehicle, and involves a proportionally increased expenditure of power in moving it. Since the field-magnets are the heaviest part of the machine, the greatest reduction in the gross weight can be effected most readily by reducing the mass of iron in the field-magnets, and for this reason some motors have less massive magnet cores than purely theoretical considerations might dictate. Again, in constructing a motor, even more care must be exercised than with a dynamo in rendering the armature able to resist sudden heavy stresses without risk of damage, the reason for which will be more apparent presently.

We have already learned that when a conductor moves through a magnetic field in such a manner that it cuts the lines of force transversely, an E.M.F. is induced in the wire, this E.M.F. depending upon the density of the field and the velocity of the wire ;

the cause which sets the wire in motion being quite immaterial. And if an independent current is already flowing in the wire, the electro-motive force induced by the motion will either tend to increase or decrease this current, according to its direction. Now when a wire, free to move, is placed in a certain position in a magnetic field, and a current is sent through it, it quickly moves to a new position. But in the very act of moving across the field, the wire cuts the lines of force, and an electro-motive force is consequently induced in it. The fact that the lines of force so cut by the wire form part of the same field which gave rise to the motion makes no difference in the result. The direction in which this electro-motive force, due to the movement of the wire, will be impressed may readily be predicted for every conceivable case, because, as such reactions always tend to stop the motion of the moving body, and as any reduction in the current must necessarily reduce the force with which the wire is moved (by the mutual action between the fields) the induced E.M.F. must always oppose and reduce the current which is flowing.

In consequence of this 'counter-electromotive-force,' the current which a given external source of E.M.F. can send through a motor is not determined solely by the resistance, but varies with the speed at which the wire of the movable part of the machine is at the moment cutting the lines of force of the field. When the revolving part, that is to say, the armature, is forcibly restrained from moving, no counter E.M.F. is set up, and the current is then at its maximum, being simply the quotient of the E.M.F. divided by the resistance. But when the armature is allowed to move, a gradually increasing counter E.M.F. is set up, and the current immediately falls in value. The higher the speed at which the armature rotates, the greater does the counter E.M.F. become, and consequently the feebler is the strength of the current. This may be observed experimentally by placing an ammeter in circuit with a battery and a motor, and then varying the speed of the latter.

Now, any one of the dynamos hitherto described can be used as a motor. For instance, we may take a direct-current series-wound machine, and, by simply passing a current through it from a battery of secondary cells, can cause the armature to rotate

rapidly. The force with which the armature moves, or the twisting-force or 'torque' which it experiences, depends upon the strength of the fields produced by it and by the field-magnet, and these in their turn depend upon the strength of the current.

The internal resistance of a secondary battery is very low, and if that of the machine is also low, an enormous current will pass while the armature is at rest; sufficiently strong, if maintained for any length of time, to damage it. But immediately the armature begins to move, this enormous current falls, until presently the speed of rotation and the counter-electromotive-force may become so high that only a very small current can flow, the torque being, of course, also considerably reduced. This variation is extremely convenient in some cases; for example, when a motor is employed to propel a tram-car, it is required to exert very much greater power to start the car from rest, than to keep it in motion after it has been started. It is just when the car and the armature of the machine are at rest that an enormous current can be sent through the machine, and a correspondingly great power exerted on the shaft; while the current falls to a safe value when a start has been effected, and before any damage can be done to the machine by over-heating. The necessity for its being able to resist such sudden heavy stresses as that caused by the effort to start with a heavy load, requires exceptional care to be exercised in the mechanical construction of a motor armature, especially with a view to prevent the stripping of the conductors from the core. Special attention is here directed to the machine illustrated in fig. 197; in which the armature conductor lies in deep narrow slots in the core, every plate of which bears directly against the shaft, the whole construction being such as to render the armature able to withstand an enormous torque without injury.

The term 'torque' is frequently employed, and merits some further consideration, especially in its application to the case of a motor armature. It is, as has been indicated, the twisting-force which an armature or other similar arrangement experiences, and represents the effort made to cause rotation. This effort is made up of two components, first the pull, which may be measured in pounds, applied at a point at a given distance from the centre of the shaft; secondly, the length of the arm at which this pull acts—

that is, the distance, measured in feet, of the point at which the pull is applied, from the centre of the shaft. Suppose, for example, the radius of the armature were 6 inches and a pull of 20 pounds were applied at a point on its circumference in a direction at right angles to the radius, then the torque, or the effort thus made to rotate the armature, would be $20 \times 0{\cdot}5 = 10$ pound-feet. If the diameter of the armature were doubled, thus giving an arm or radius of 1 foot, the torque would also be doubled, being $20 \times 1 = 20$ pound-feet, and so on. In the case of an actual armature the pull is exerted not at a single point on the circumference, but at a number of equidistant points—at every armature conductor, in fact—and as the distance of every conductor from the centre of rotation is the same, the resulting torque may be found by multiplying together the sum of the pulls on all the conductors by the radius, or their common distance from the centre of rotation. For example, if the number of active conductors round the circumference were 100, the pull on each 15 pounds, and the diameter of the armature 18 inches (radius 9 inches $= {\cdot}75$ foot), the torque would be $100 \times 15 \times {\cdot}75 = 1{,}125$ pound-feet.

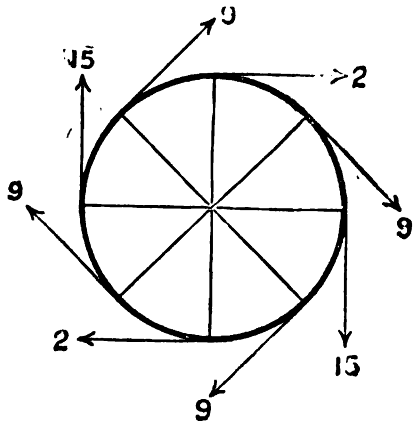
In no case, however, is the pull or drag experienced by an armature conductor the same at all points of its circular path through the field. In the first place, the field varies in strength at different parts of the path through which the conductor sweeps; and then the current in every section of the armature falls to zero for a moment while its particular commutator bars are passing under a brush, so that during that moment the pull on the conductors of that particular section is *nil*. The value of the pull on the conductors round a motor armature varies, in fact, in much the same way that the activity of the conductors round the surface of a dynamo armature changes, being at a minimum along the diameter of commutation, and rising to a maximum at right angles thereto. It will also be evident that the counter electromotive-force developed by every individual conductor rises and falls in value with the drag upon it, being equal at any moment to that electro-motive force which it would develop if the armature were driven mechanically as a generator and lines of force were cut effectively at the same rate.

The sum of the separate forces acting on every armature

conductor remains, however, constant in value, because as each conductor passes from the position of greatest activity its place is taken by another, and so on. But we can only make such a calculation as that just given by first calculating the total force or pull acting upon all the conductors at any moment, and then dividing by the number of conductors in order to obtain the average force or pull on one conductor.

In fig. 234 we have represented a state of affairs more nearly approaching to that which obtains in an actual armature, where the diameter of commutation may be taken as being a few degrees

FIG. 234.



from the vertical, and for simplicity only eight active conductors are indicated. The pull on each conductor acts at right angles to the diameter of the armature passing through that point, because the lines of force nearly all enter at right angles to the surface of the armature core, and every conductor is urged across the field at right angles to the lines of force. Even were this not so, the reduced resultant force acting at right angles to the diameter would be the force which we should have to consider, since it would be the only part of the total force acting effectively to rotate the armature. The figures placed against each arrow-head represent the pull in pounds experienced by each armature conductor, and each conductor is at the moment impressing upcn the

shaft a torque or twisting-force equal to its particular pull multiplied by the length of the arm at which it acts—that is to say, its distance from the centre of rotation. Let this distance or radius r equal 6 inches; then, since each pull acts in the same direction, the total torque is the sum of these separate values, or

$$2r + 9r + 15r + 9r + 2r + 9r + 15r + 9r$$
$$= (2 + 9 + 15 + 9 + 2 + 9 + 15 + 9)r$$
$$= 70r = 70 \times \cdot 5 = 35 \text{ pound-feet.}$$

This proves the statement previously made, that the torque may in any case be estimated by multiplying the sum of the pulls on each conductor in pounds by the radius of the armature measured in feet or a fraction of a foot.

As a simple practical example we may assume the case of a motor armature 12 inches in diameter (6 inches radius) with 100 active conductors, and giving on the shaft 12 horse-power when the speed is 500 revolutions per minute. The whole of this power appearing on the armature shaft is first transmitted by the conductors through the core to the shaft, and from the figures given we will discover first the torque and secondly the average pull in pounds on the conductors. One horse-power is equivalent to a rate of working equal to 33,000 foot-pounds per minute, and consequently we have in this case a rate of working equal to $12 \times 33{,}000$ or 396,000 foot-pounds per minute.

The whole of this power being impressed upon the armature conductors, we can, if we know the distance in feet through which they travel in one minute, divide by this distance, and obtain the force in pounds exerted at any moment on the whole of the conductors. Any one conductor in every revolution travels round a path equal to the circumference of the armature ($2\pi r = 2\pi \times \cdot 5 = 3 \cdot 14$ feet) and passes therefore through $500 \times 3 \cdot 14 = 1{,}570$ feet in one minute when the armature makes 500 revolutions per minute. Consequently the actual pull exerted upon the armature conductors is $\frac{396{,}000}{1{,}570} = 252$ pounds. From this we see that the torque must be $252 \times \cdot 5 = 126$ pound-feet, and the average pull per conductor $2 \cdot 52$ pounds.

The pull on any one conductor when at the most active part of its journey amounts to a much higher value than this average pull; and in a powerful machine the value becomes exceedingly high, especially when, as at starting, the back electro-motive force is *nil* and the current through the armature becomes abnormally high. These considerations emphasise the necessity for an effective mechanical connection between the conductors and the armature core, which can be secured either by a liberal use of driving horns or, better still, by embedding the conductors in slots in the armature core.

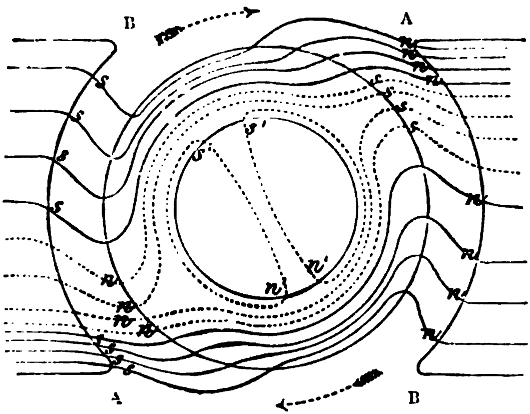
Supposing the field to be the same in both cases, the direction of the current in the armature of a machine when used as a motor must be the reverse to its direction when used as a generator, if the direction of rotation is desired to be the same in each case; indeed, we have just seen that the counter E.M.F. generated is opposite to that which produces the driving current. Therefore, if the direction of the driving current applied to the terminals of a series machine is the same as that which would be developed by the machine itself, the connections either of the armature or of the field-magnets must be reversed; or if a rotation in the opposite direction is desired, the connections should be left unaltered, and the brushes turned round to suit the reversed rotation. A shunt dynamo, on the other hand, will, without any alteration, turn in the same direction if an E.M.F. opposite to that developed by it as a generator is applied to its terminals, for the current through the armature is then in the reverse direction, while that through the field-magnet coils is the same as before. This will be apparent on inspection of the diagrams of the shunt-dynamo connections given in figs. 161 and 162; when employed as a generator the field-magnet coils form a shunt to the external circuit, but when used as a motor these coils act as a shunt to the armature.

The distortion of the field observed when a machine is used as a generator also occurs when it is employed as a motor, because, when the brushes are at zero, the lines of force of the armature field are at right angles to those of the field-magnets. But the direction of the current, and therefore of the lines of force, being reversed in the case of a motor armature, the direction of the

resultant field is also different. The amount of the distortion depends, obviously, upon the relative strengths of the two fields. It is very slight when the field-magnets overpower the armature, but in all cases the direction of the resultant field is such that the brushes must be shifted *backward* to place them on a diameter at right angles to the lines of force, and so to avoid sparking.

The distortion of the field of a motor is illustrated in fig. 235, which should be compared with the corresponding figure (158) for a generator. The density of the lines of force is greater at the horns A A which the armature is approaching, and, as a consequence, any irregular distribution of iron in the armature core

FIG. 235.



causes stronger eddy currents, and develops more heat at these places than, as in the case of a dynamo, at the horns B B from which the armature is receding. With an ordinary armature having a smooth core this heating is hardly appreciable, and in all cases it is influenced to a certain extent by the fact that a current of cold air is drawn in at A A and ejected somewhat warmer at B B. In the case of a motor, therefore, this air current tends to reduce, and in the case of a generator to increase, the difference of temperature between the two horns of each pole-piece.

The current through the armature of a motor frequently varies considerably, and this may cause a shifting of the resultant field,

and therefore also necessitate an alteration in the position of the brushes ; but in all cases a reduction in the angle of lead, and immunity from sparking due to a variation of the armature current, may be obtained by employing a very powerful field relatively to that produced by the armature. But this necessitates considerable weight, especially in the field-magnet cores. Hence the superiority of wrought-iron of high permeability is apparent, although even when this is used the weight of a motor built upon this principle is still considerable. As we shall see presently, it is possible to construct a light but efficient machine by so arranging matters that the armature field shall be very powerful and reinforce that of the field-magnets, special precautions being taken to prevent the sparking which would otherwise ensue. But at the same time it must be remembered that the advantages arising from the use of powerful field-magnets, even at the expense of extra weight, are not lightly to be thrown away ; and that in ordinary cases it is rarely true economy to sacrifice much in order to save a little weight.

The electrical power may be supplied either at a constant pressure, or with a constant current ; in the former case regulation is comparatively easy, while in the latter greater economy in the distribution of power can sometimes be effected. Supposing a constant potential to be maintained at the terminals of a shunt-wound motor ; the current through the field-magnet coils will always be the same, and therefore the strength of the field remains constant, but the current through the armature depends upon the speed of rotation, being, in fact, determined by the excess of the applied electro-motive force over the counter electro-motive force. Supposing the machine to be employed in driving a tram-car ; then, for example, when the car commences to mount an incline, the armature shaft is called upon to perform additional work, which tends to reduce the speed of rotation. This reduction of speed, by reducing the counter electro-motive force, immediately allows a stronger current to pass through the armature, and affords the necessary electrical power to perform the extra work. On the other hand, should the car be allowed to attain a high speed in descending an incline, the counter E.M.F. would reach a high value, so high in fact that very little current would pass through

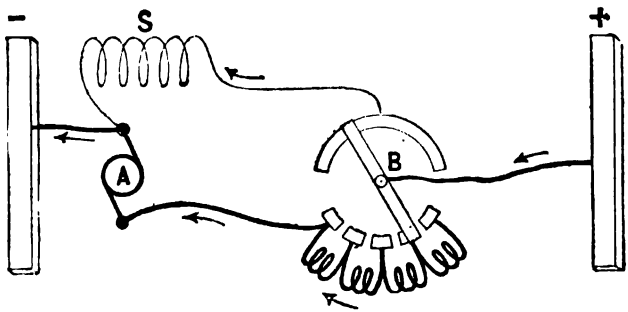
the armature, whence very little electrical power would be expended. The demand upon the source of the electrical power is thus to a certain extent automatically regulated in a very simple manner according to the requirements, and this effect of the counter electro-motive force obtains whatever the purpose may be for which the machine is employed.

If the armature resistance is extremely low and that of the shunt-coils high, and if the field-magnet develops a much greater field than the armature, the variation of lead will be but slight, and, further, the machine will to a great extent be self-regulating as regards speed.

Many motors now constructed satisfy these conditions sufficiently to render any other aids to regulation superfluous. But some precautions are needed in joining such machines in circuit, especially if, as is usually the case, any load is applied to the shaft before the armature has approached its normal speed. Even though the potential difference between the mains to which the machine is to be connected were no more than 100 volts, this would give rise to an enormous current through the armature, before it had time to get up speed and develop the counter E.M.F. which would be competent to reduce the current to a safe value. The armature while at rest would in fact simply short-circuit the mains and the field-magnet coils, and the latter fact would, by preventing the rapid establishing of a powerful field, tend to retard its getting up speed. In any case the field-magnets, if massive, take an appreciable time in becoming fully magnetised, and it is advisable to start such a shunt-wound machine by first joining the field-magnet coils directly across the mains, then joining the armature in series with a considerable resistance across the mains, gradually cutting out this resistance as the armature rises in speed. Such an arrangement is indicated in fig. 236, where A represents the armature, S the field-magnet coils, and B a switch with four resistance coils, the positive main being shown on the right and the negative on the left. One end of the metallic switch bar or lever, which is connected to the positive main, passes over and makes good contact with a curved brass strip which is joined to one end of the field-magnet coils; the other end of the bar passes over five brass studs, to which the resistance coils are connected

as shown. In order to disconnect the motor and stop it, the switch bar should be turned left-handedly through about 60° from the position shown, when it would lie clear of the studs and also the curved bar. To start the motor the bar must be turned right-handedly from this position of disconnection, when its upper end will first make contact with the curved strip, thus allowing the current to pass through the coils S and excite the field-magnet. It will be observed that this end of the bar makes contact with the curved strip and completes the field-magnet circuit before its other end makes contact with the extreme right-hand stud; but by further turning the switch bar in the same direction, the lower end makes contact with this stud and completes the armature circuit, all the resistance coils being then in series with it. The

FIG. 236.



resistance coils have such a value that even were the armature not to start the current would be insufficient to damage it, and the coils themselves are made of wire (preferably bare German silver) sufficiently thick to carry the maximum current. When a current is thus started through the armature, it should at once commence to rotate and develop a counter E.M.F., and the switch bar can then be moved on to the next stud (the position indicated in the diagram), when only three coils are in series with the armature, which, under the influence of the more powerful current, rotates yet faster, and the switch bar can be finally moved up to the extreme left-hand stop, when all the resistance will be cut out of circuit and the armature joined direct across the mains.

In some cases where exceptionally good regulation is desired,

and where the armature resistance cannot well be made sufficiently low and the field sufficiently powerful to secure it, other devices may be employed. We have seen that when an additional load is thrown on the motor, the resulting reduction in speed immediately allows the passage of a stronger current through the armature ; but if the speed is to be kept constant, the counter electro-motive force will also be constant, and then the current through the armature can hardly vary at all, so that the two conditions are opposed to each other. But by reducing the strength of the field developed by the field-magnets, the counter E.M.F. can also be reduced, and therefore a stronger current can be passed through the armature when rotating at a given speed. It is necessary, then, to devise some means of reducing the strength of the field when the load is increased and the current in the armature rises. The simplest way of accomplishing this is to place a few turns of thick wire round the limbs of the field-magnet, in series with the armature, but wound in such a manner as to magnetically oppose the shunt-coils, instead of assisting them as in the case of a compound wound generator. The effect of these series-turns in weakening the field becomes greatest when the armature current is strongest, and *vice versâ* ; but it should be observed that since the strongest current which can pass through the armature (and therefore also the series-winding) does so when it is at rest, the armature may start in either direction, as determined by the shunt-coil field or the field produced by the heavy current in the series-windings. To avoid any uncertainty, it is usual to lead the ends of the two windings and of the armature separately to the switch-board, and to reverse the current through the series-windings, so that both shunt- and series-coils act together in developing a strong field in the right direction at the moment of starting, the series-turns being joined up in the normal manner when the speed rises above a certain value. The series-turns, being few in number, aid the shunt-coil but little when in series with it because they are then carrying a small current ; and practically the same result may be obtained by simply short-circuiting the series-coils until the machine has been properly started.

The field of a shunt motor may also be weakened by inserting resistance coils as required, either by hand or automatically, or by

altering the ampere-turns in any other manner. It appears at first sight somewhat paradoxical that the speed of a motor can be increased by reducing the strength of the field, but the reduction of the counter electro-motive force allowing a more powerful current to be urged through the armature, as mentioned above, satisfactorily explains the matter.

The case for a series motor fed with a constant current is different, and the distinction must be clearly borne in mind. If the load is decreased, the speed increases, and so gives rise to a higher counter E.M.F., but the generator responds to this and by developing a correspondingly higher E.M.F. maintains the current constant. Consequently the speed of the machine increases enormously when the load is lightened to a great extent, and it is then that unless care is taken considerable damage may be done. If it be desired to reduce the speed or the power given out by a series motor fed with a constant current, this may be readily effected by diminishing the strength of the field, since in this case the armature current is kept constant under all conditions. The resulting reduction in the counter E.M.F. simply causes the generator supplying the current to develop a lower E.M.F., because a lower pressure at the terminals of the motor becomes sufficient to urge the proper current through it.

The alteration in the strength of the field is conveniently effected by shunting the field-magnet coils with a variable resistance, and the application of one such method will be considered presently.

Only a portion of the power given electrically to a motor is converted usefully into mechanical power, a part being spent in heating the armature, field-magnet coils, &c. When the armature is held at rest the whole of the electrical power absorbed by the motor is thus converted into heat, and the efficiency of the machine —that is, the ratio of the useful power obtained on the shaft to the total power supplied—is then at its lowest value, viz. nought. When the armature is allowed to move, the useful performance of work begins, and as the current also falls in strength, the power wasted in heating decreases. The higher the speed of rotation, the higher becomes the counter E.M.F. and the less becomes the power wasted as heat in the conductors ; in fact, the ratio of the

power usefully absorbed by the motor to the whole power supplied is very nearly proportional to the ratio of the counter E.M.F. to the E.M.F. applied at the terminals of the machine. The efficiency of the machine is therefore highest when the load is a minimum, that is, when it is doing least work per revolution, while the torque, or the force with which the armature tends to rotate, is greatest when the load is sufficiently great to prevent the armature turning, and when, therefore, it is doing no external work at all. Now, when a motor is running at a high speed and with a comparatively feeble current through the armature it performs very little work indeed during one revolution, although, the number of revolutions being great, a considerable amount of work may be performed during a given interval of time, say one minute. On the other hand, when the speed is very low the amount of work per revolution is comparatively great, but the small number of revolutions per minute prevents the quantity of work reaching during that interval a very high value. By considering these two extreme cases, it might be supposed that there is a certain intermediate speed of rotation at which the work performed by any given motor is a maximum. This is the case, and the speed of a motor at which it can perform the maximum amount of work per minute is that speed at which the counter electro-motive force becomes equal to the electro-motive force applied at the terminals. This result is quite independent of the *efficiency* of the conversion, which, as we have seen, increases with the speed of rotation, and the efficiency of any motor when it is doing the maximum amount of work which it can do, is so low (about 50 per cent.), that in practice motors are not worked under such conditions for any length of time.

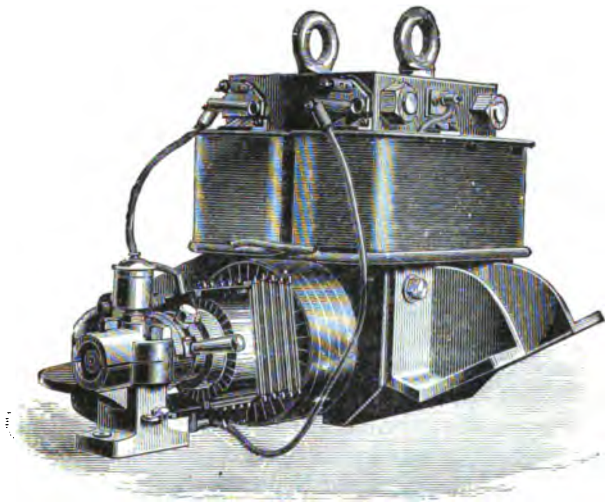
We are now in a position to consider the construction of various types of motor and of the methods of applying these motors to the various classes of work which they are competent to perform.

In fig. 237 is illustrated a motor which was constructed by Messrs. Easton, Anderson & Goolden for an electric launch. The field-magnet is of the single horse-shoe shape, the cores being of wrought-iron, secured to a wrought-iron yoke-piece by two horizontal bolts. On the outer side of each pole-piece is a gun-

metal supporting bracket with two flanges, shaped to fit the ribs of the boat. One bracket (that at the back in the figure) is extended on either side to form the bearings for the armature shaft.

The machine is shunt-wound, the field-magnet coils consisting of 2,680 convolutions of No. 14 S.W.G. copper wire, having a resistance of 6·96 ohms. The armature is of the drum type, and is wound with two No. 14 S.W.G. wires in parallel, there being 216 convolutions of this double wire, giving a resistance from brush to

FIG. 237.



brush of 0·2 ohm. Each section has six turns, so that there are thirty-six bars in the commutator, which is insulated throughout with mica. The adjacent end of the armature is covered by radial extensions of the commutator bars, the mica insulation being also extended to the periphery. The other end of the armature is covered by a metal plate of an equal diameter, the rest of the armature being enveloped by a waterproof material securely bound on, so that the whole is rendered completely watertight. The armature shaft is, at the end remote from the commutator, coupled direct on to the shaft of the propeller. The

armature brushes and the field-magnet coils are connected to separate terminals leading to the controlling switch, and the motor is reversed by simply reversing the direction of the current through the armature. To render this practicable, the brushes are of a special type (see fig. 243), consisting of steel springs placed flat against the commutator, and provided with solid carbon blocks for making contact, the requisite pressure being given by india-rubber bands passing round hooks at the ends of the springs. This motor develops five horse-power when running at 500 revolutions per minute; the current is supplied by secondary cells, the machine being designed to carry 50 amperes at 95 volts as a normal load, while it can safely take up to 70 amperes when necessary without risk of damage by over-heating.

The efficiency of this motor is about 85 per cent., which is high for such a small motor at the comparatively low speed of 500 revolutions per minute.

In most cases the difficulty of obtaining a machine of reasonable efficiency at a low speed, without abnormal proportions and correspondingly heavy weight, renders it necessary to run at a high speed, and to effect the reduction required, by suitable gearing. Thus, for example, the wheel of an ordinary tram-car travelling at seven miles per hour does not revolve at so high a speed as eighty revolutions per minute, and it would be impossible to construct a practical motor to run at this low rate. A machine running at 720 revolutions might be employed, by introducing gearing which would reduce this speed to about one-tenth. The selection of suitable gearing is not, however, an easy matter, for it must be light, strong, and durable, and should produce neither noise nor vibration in working; and, while absorbing little power in friction, it must be capable of withstanding dust and dirt, or of being easily protected therefrom. Some very good devices, depending upon friction to transmit the power from a small wheel on the rapidly rotating armature shaft to a larger pulley on the axle, have been employed with fair success on lines where the gradients are slight; but where the power required to be transmitted is at times very heavy, this method is not to be relied on. By means of a pinion and spur-wheel, with or without an intermediate counter-shaft, very great power can be transmitted.

One great objection to this gearing is that it is noisy; the teeth of the pinion on the armature shaft also rapidly show signs of wear.

The necessary reduction in speed can also be obtained, and in a very satisfactory manner, by means of a screw and worm-wheel; a screw, driven by the motor shaft, gearing into the teeth of a worm-wheel on the axle of the car or on a counter-shaft. Chain gearing is also employed; in this case an endless chain passes over a small toothed wheel on the motor shaft and a larger one on the axle, the teeth of the wheels fitting into the links of the chain. The chain is, however, liable to stretch, and then the teeth no longer fit accurately, and slipping is likely to take place.

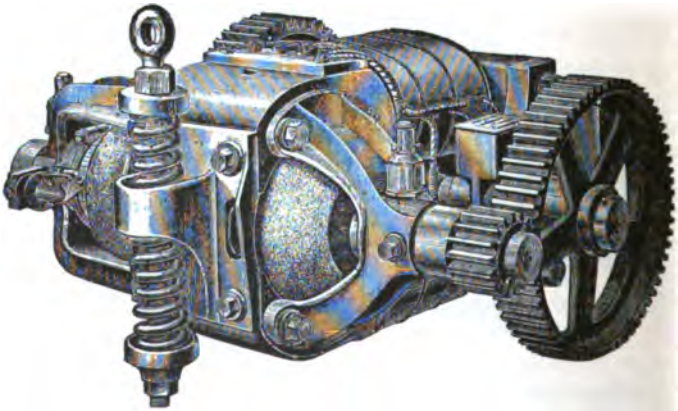
FIG. 238.

In figs. 238 and 239 a good example of spur-gearing is illustrated. The motor, designed by Lieut. Sprague, is intended for use on a tram-car, the field-magnet being of the single horse-shoe type, and of wrought-iron throughout. At the yoke end, the motor is swung from the axle of the car, this bearing being shown to the left of fig. 238, while at the other or armature end, it is flexibly supported, being attached to the body of the car by means of the spring shown in fig. 239. Bronze brackets, fixed to the pole-cheeks, support the armature bearings, and a pinion on the armature shaft, as indicated in fig. 239, gears with a spur-wheel carried on a counter-shaft which passes between the limbs of the field-magnet. At the other end of the counter-shaft is the pinion visible in fig. 238, which gears into a spur-wheel keyed on to the

axle of the car, the number of teeth being so proportioned, that the speed of rotation of the axle is about one-twelfth of that of the armature.

The pinion on the armature shaft is sometimes made of hard vulcanised fibre. The wear is, of course, greatest at the teeth of this pinion, while the greatest power is transmitted individually by the teeth at the other end of the train. The teeth are, however, strong enough to resist a *steady* pressure far greater than can be given by the machine; were the full power suddenly applied with a jerk, the strain would be enormously increased, but a most important function of the supporting spring is to prevent

FIG. 239.



this jerk taking place, by yielding slightly when the pressure is suddenly applied. But the advantage gained in this way entails the disadvantage that the distance between the centres of the engaging wheels is liable to variation. Consequently, involute teeth are employed—that is to say, the form of the rubbing surfaces of the teeth is the involute of a circle, such teeth being the only ones which are independent of an alteration in the distance between the centres of the wheels.

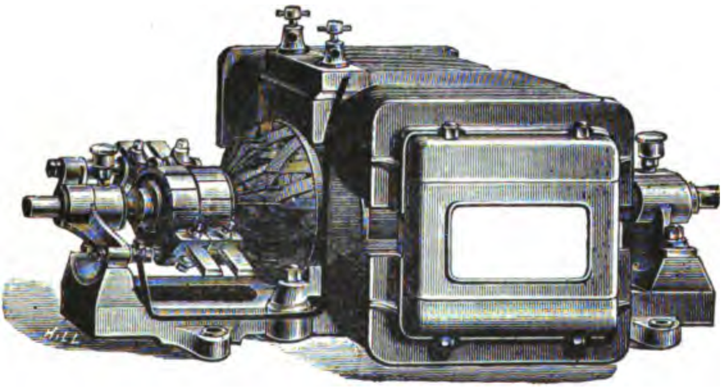
The armature is entirely covered with a waterproof material, and the field-magnets being also protected by an impervious covering, the machine is but little liable to injury from moisture.

The covering of the field-magnets consists of sheet copper, the joints being carefully sealed. An advantage attending this arrangement is, that the heavy current induced in the low resistance copper sheathing whenever the current in the field-magnet coils is considerably varied, reduces to a very great extent the magnitude of the extra current developed in the coils on suddenly breaking the circuit.

Carbon brushes are employed, the commutator being of the usual form, viz. copper bars insulated with mica.

In fig. 240 is illustrated the Immisch motor, a type which possesses some important peculiarities. The field-magnets are of

FIG. 240.



the double horse-shoe form, the coils being wound in four sections on the horizontal portions of the core, although in a few instances two coils only are employed, wound on the vertical limbs, as in the case of the Manchester dynamo.

In these machines the magnetic field developed by the armature is comparatively powerful, being equal to, or even greater than, that developed by the field-magnet, the object being to effect a great reduction in weight. As has been already remarked, it is possible, since the two fields reinforce each other, to employ a weak fixed field and yet obtain the necessary torque on the armature, provided the armature field is correspondingly increased in strength; but this entails some special device to

avoid the necessity for altering the lead of the brushes to suit the variations of the current caused by a varying load. The actual requirement is, of course, to keep the direction of the resultant field unaltered, so that the brushes shall always be on a diameter at right angles to this field; and in the Immisch machine the arrangement for maintaining this constancy amounts to simply short-circuiting the sections of the armature for a considerable period as they pass the neutral position. If the field is in its normal position when these coils are short-circuited, they are practically inactive. But should the field be shifted, say by an increase of the load, the short-circuited coils cut lines of force transversely, acting as the coils of a generator, and the resistance of the closed coil being very low, the conditions for a large current are established, the lines of force resulting therefrom being in such a direction as to oppose the distortion of the field, and bring it back to the normal position. The short-circuiting is effected by the commutator, which, as shown in fig. 240, consists of two sets of segments, placed side by side, one set being fixed half the width of a segment in advance of the other.

The armature is drum-wound, and the connections are such that the two parts of the commutator might be formed into one, by interposing each segment on one half between the two facing segments on the other half. The two brushes side by side are electrically connected, forming, in fact, one wide brush, and the effect is precisely similar to that which would take place if an ordinary commutator were employed with thick brushes covering one bar.

Under ordinary circumstances the effect of an increase of the current in the armature would be to increase the distortion of the field, and therefore to necessitate a greater negative lead being given to the brushes. The immediate effect, however, in the present case is to cause the short-circuited coils to generate a powerful current, the lines of force due to which are in the same direction as those of the field-magnets, the resultant tendency being to reduce the distortion to its normal amount.

It might be expected that considerable heating in the coils would result from the short-circuiting, but this does not occur to any appreciable extent, and is probably to be accounted for by the

prompt action of the current in the short-circuited coils in restoring the field to its normal position before the current rises to a very high value. It must be remembered that the field due to the field-magnets is a comparatively feeble one, and it is in consequence much more readily affected by such changes in the armature reaction than is a machine built upon the orthodox lines.

The armature core is built up with the usual thin iron plates, which are insulated with asbestos, thick rigid plates being placed at intervals, and having projections above the surface of the rest of the core, which act as driving horns.

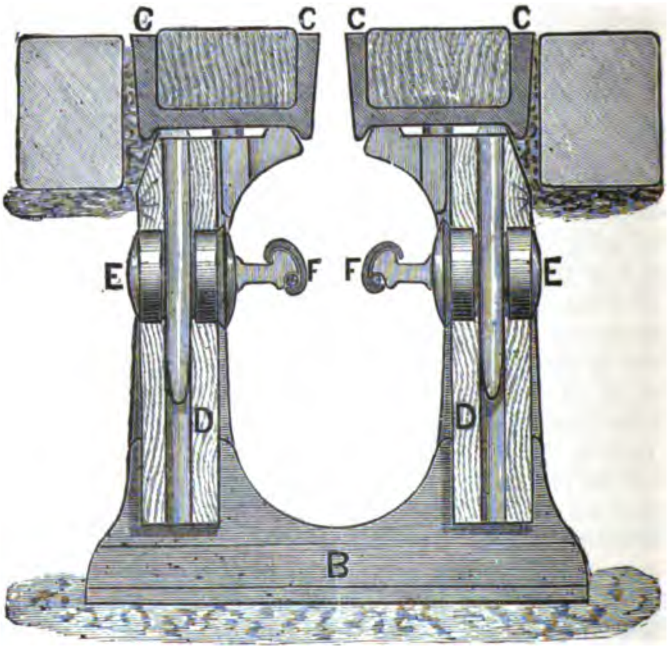
The machines are usually series-wound, and are made in a variety of sizes for different purposes. One, designed for driving a tram-car, weighs $5\frac{1}{2}$ cwt., and is intended to run at 1,000 revolutions with a current of 40 amperes at 60 volts. The gearing consists of two steel chains with a counter-shaft, the reduction of speed being 10 to 1 ; the velocity of the chain on the armature shaft is, at times, as high as 2,000 feet per minute, and the high speed of the motor allows a considerable reduction in the weight of the machine. The current is supplied by eighty secondary cells carried on the car, a switch being provided for connecting these, either all in series, or forty in series and two in parallel, so as to vary the power given to the machine. The same switch can also be used to throw resistance in circuit, when the motor is being started, to prevent the passage of a too heavy current before a counter E.M.F. is generated. The direction of rotation is reversed by reversing the current through the armature, two sets of brushes being provided, operated by a suitable lever, one set adjusted with a slight negative lead in one direction, and the other set with a corresponding lead in the reverse direction.

One of the earliest and most successful applications of the electric motor for traction work was made by Mr. M. Holroyd Smith, on the Blackpool Electric Tramway. This venture was made in the experimental days of electric traction, and great difficulties were contended with and overcome. The working has been so successful under somewhat trying local conditions as to prove that the system is sound, and we shall accordingly briefly describe the main features. The line is two miles in length, and consists chiefly of a single track with a number of pass-byes. It

runs along the sea-coast in such an exposed position that the road is occasionally flooded during the winter months, and at all times the saline deposit, which is always prevalent near the coast, considerably enhances the difficulty in insulating the conductors.

The conductors are laid underground in a channel midway between the two rails on which the car wheels run, the current

FIG. 241.



being taken from them to the motor, by means of a collector trailing through a narrow opening in the top of the channel.

In fig. 241 a transverse section of this channel is shown, the main support being afforded by cast-iron chairs which are fixed at intervals of a yard. One of these chairs, B, is shown in the figure; its height is 11 inches, base $12\frac{1}{2}$ inches, and internal width $5\frac{1}{2}$ inches; it has vertical slots cast in it, on each side, and into these slots are fitted stout creosoted boards, D D, which form the sides

of the channel. Steel troughing, C C, runs along and is bolted to the tops of the cast-iron chairs. This troughing is then filled with wooden blocks to form the paving of the road; the remainder of the paving being also of wood. The sides of the steel troughs slope slightly, so that the opening between them widens from half an inch at the top to one inch at the bottom, in order that a stone on getting in may fall through instead of being wedged in. The conductors are strips of hard-drawn copper, of the shape shown at F F; the sectional area of each is equal to a solid rod, 0·575 inch in diameter, and its resistance is 0·165 ohm per mile. The strip fits over an iron stud, the under side of which is grooved, and a wooden pin is driven in, to fix it securely in position. This stud is cemented into a cylindrical porcelain insulator, E, having a deep groove round its periphery, and holes 2½ inches in diameter are bored in the wooden sides of the channel midway between the chairs, for the reception of these insulators. A ¾-inch vertical hole is also bored in the wood on one side of the insulator, and into this a wooden peg is driven, which, passing downwards through the groove, locks the insulator fast. More recently glass studs cemented into a porcelain insulator have been adopted.

The various lengths of the conducting tubes are electrically and mechanically connected by two wedges of drawn brass (not shown in the figure), which, when driven tight together, exactly fit the inside of the tube, the compound wedge being wrapped with wire to prevent it shifting. A little space is left between the ends of adjacent sections of the tubes to allow for expansion and contraction, which is, of course, considerable; in fact, the connecting wedges cannot be soldered to the tube, as the expansion due to the difference in the temperature at night and noon would crack the solder. The two parallel conductors, F F, form a single positive lead, and the collector places them in connection with one terminal of the motor, whose other terminal is connected to the wheels of the car, the return circuit being made through the rails, or, rather, by means of the rails through the earth. The two tubes are electrically connected at every hundred yards by a loop of insulated and lead-sheathed copper wire, placed in a groove cut in the sides and bottom of the channel. The resistance of the positive lead must be taken as that of the two tubes in parallel,

and if the rails make good earth at every point there will be practically no resistance between the negative terminal of the motor and the negative terminal of the generator, which is also connected to earth. But this would rarely or never happen, and to avoid any serious resistance at the junctions, adjacent rails are electrically connected by a strip of copper, the ends of which are plugged into holes punched in the rails.

The engines and two generating dynamos are placed at the middle of the line. The generators are four-pole machines, each being separately excited by a small machine; a set of resistances is placed in circuit with the exciter and field-magnet coils, by varying which the strength of the field, and therefore, also, the E.M.F. developed by the generators, can be altered at will. The maximum E.M.F. of each is 300 volts, and the current 180 amperes. The two machines are when required run together in parallel.

The maximum potential difference, viz. that at the middle of the line, is about 220 volts, and this falls gradually towards the two extremities. The deposit of moisture previously referred to is sometimes so great as to cause a serious leakage after the line has been standing idle during the night; in the earlier days this leakage amounted at times to 100 amperes, but the passage of the heavy current rapidly increases the insulation. Such improvements have been effected that the loss during working hours does not now, under ordinary circumstances, exceed 3 amperes.

A good idea of the salient features of the system may be gathered from fig. 242. The collector, which is designed to run equally well in either direction, consists of two slanting clearing ploughs of tempered steel, connected by hinged wrought-iron plates to a centre-piece. This centre-piece consists of a cast-iron cheek, bearing on the edges of the steel troughing, and having fixed vertically through it a strong brass strip, which is well insulated and protected by hardened steel guards where it passes through the slot. The bottom of the strip is bare, and has fixed to it a short horizontal brass arm, which carries at each end two curved hard metal wings, facing in opposite directions, and each partly embracing one of the conductors. The whole forms a combination which is flexible enough to turn sharp bends, such

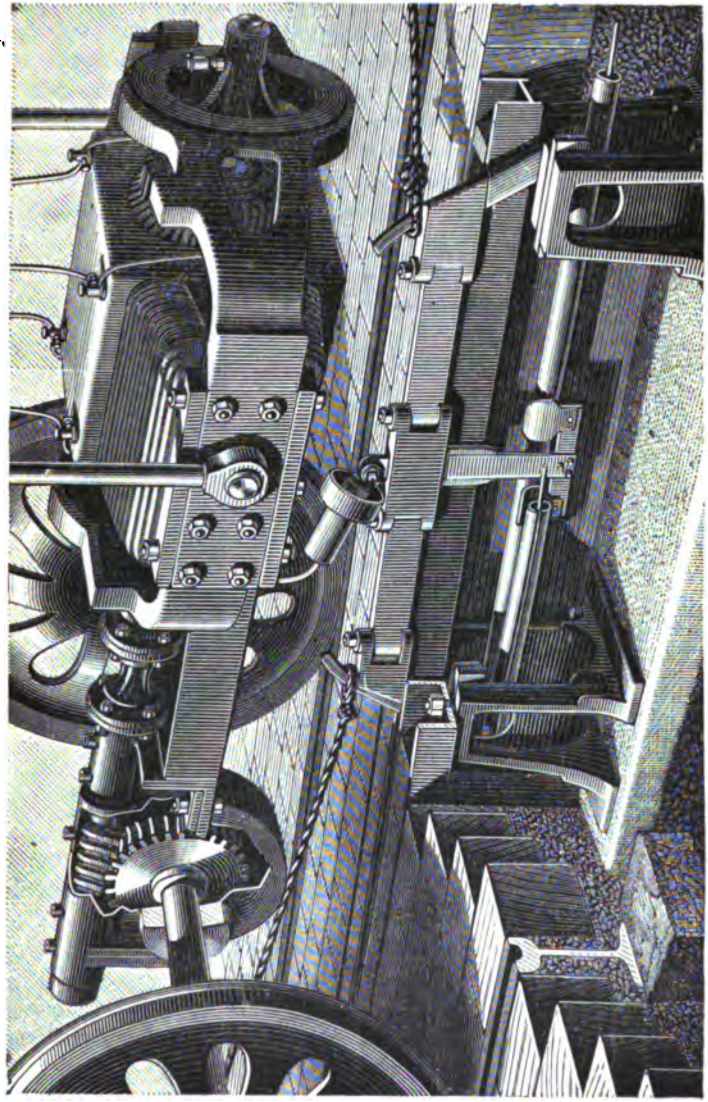
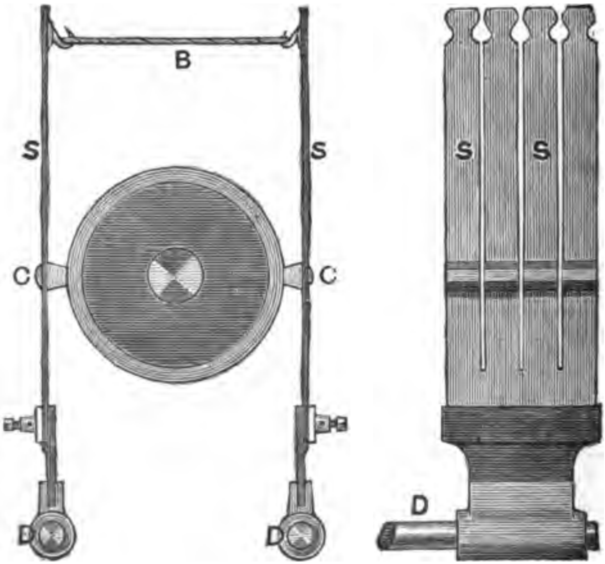


Fig. 242.

as those at crossing points, is capable of clearing the opening of any slight obstruction, and ensures good electrical contact with the conductors. Each of the steel ploughs terminates in a finger, on to which is hooked a hauling rope, attached to the body of the car, but a loop of weaker cord is inserted, so that if the collector meets with a serious obstruction this loop breaks, the car passes on, and can be quickly brought to a standstill by the ordinary brakes. The loop slips off the trailing finger, and a detachable

FIG. 243.



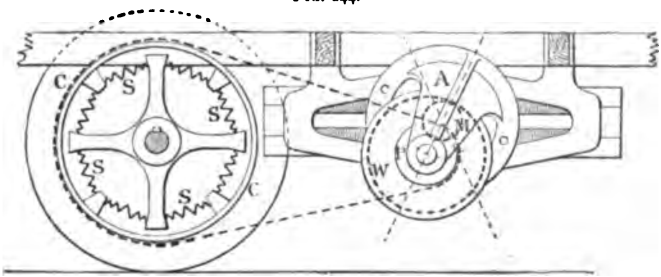
electrical connection is also provided, consisting of a clip, bored to receive a heart-shaped terminal, which can easily be inserted, but requires a rather sharp jerk to release it.

The motors are series machines, the field-magnet cores being of good wrought-iron, and no practical advantages have been sacrificed for the sake of obtaining an extremely light and electrically efficient motor. The field-magnets develop a very powerful field, and the space between the iron of the armature core and the pole-faces is very small, the armature conductor consisting of one

layer of silk-covered wire; consequently a comparatively weak armature field can be employed, and the distortion is inappreciable. In fact, the brushes can be allowed to make contact at the same place for either direction of rotation, without any appreciable sparking. This admits of the employment of an extremely simple and effective type of brush, which was invented by Mr. Smith for the purpose of enabling the armature to be run in either direction without any alteration of the brushes, and to avoid the jolting of the car breaking contact.

Two views of these brushes are given in fig. 243. D D are the spindles passing through the holders to which electrical connection is made, S S being a thin flat steel spring, divided into four strips. The extremities of the springs are connected and drawn together

FIG. 244.



by india-rubber bands, B, and a small block of hard metal, C, is fixed to the middle of each strip, forming the contact with the commutator. This type of brush is, perhaps, the simplest and most effective that can be devised for the purpose; the wear takes place at the hard metal contact-pieces, which are so fixed that they can easily be replaced when worn out.

Fig. 242 illustrates the system as applied to a line in France, and an important feature is the worm-gearing. An endless screw gears with a wheel keyed on the axle, and the screw is connected to the armature spindle by a flexible joint, a certain amount of play longitudinally being also provided for. The screw and wheel are effectively protected by a casing, part of which is, in the figure, removed to show the interior.

The gearing employed on the Blackpool line is illustrated in

fig. 244, for permission to reproduce which we are indebted to the Council of the Institution of Mechanical Engineers.

A side view of the motor is shown, and M is a pinion at the end of the armature shaft, gearing into an internal toothed wheel, W—that is, a wheel having teeth on its inner periphery. The pitch-circles of M and W are indicated by the dotted circles. On the outside of W, that is, on the side remote from the motor, is fixed a chain pinion, P, gearing by a chain with a chain-wheel, C, which is carried on the car-axle.

The chief objection to the use of chain gearing is that the chain always gets slack after a time, but a very simple and effective arrangement is introduced to take up the slack and so overcome this objection. The wheel W is carried by an adjustable bracket or arm, A, which is centred on the motor-shaft, that is to say, the arm is capable of being rotated about a centre which exactly coincides with the centre of the shaft. Consequently, the pinion M and the wheel W remain in gear for every position of the arm, because the distance between their centres remains unaltered. The arm is locked in position by bolts passing through slots, and it is an easy matter to loosen these, rotate the arm through a small angle, and fix it in the new position, if the chain becomes slack. The placing of a new chain in position can also be rapidly effected.

A special device is also introduced to avoid a jerk at starting, which, as has been remarked, throws a severe strain on the gearing. The connection between the chain-wheel and the axle is not rigid, but is made through several stout spiral springs, which yield and take the jolt off the chain when great pressure is suddenly applied. The chain-wheel C C consists of a loose annular rim, having four inwardly projecting pieces placed midway between the arms radiating from the hub which is keyed on to the axle. The ends of the arms are connected to the wheel C by spiral springs S S, as shown in the figure, and these springs by extending allow the pressure to be applied more gradually.

The motors are series-wound, and supplied at an approximately constant potential, and the speed is regulated by the alteration of resistance joined in series with the motor; for, supposing the load to be constant, any increase of resistance reduces the current

flowing through both the armature and field-magnet coils, and so reduces the speed of rotation; while a reduction of resistance allows the current to increase, and therefore also the speed. The same resistances can also be used to regulate the strength of the current required in starting. The aim has been to make the arrangement practical and workable without risk of error or damage by an inexperienced driver, and also to allow the variation of resistance to be made gradually, without employing a large number of coils. It is also necessary to provide a large surface for radiation in the case of the lowest resistances, because they have to carry a heavy current, and the heat generated is considerable. All these points are effectually provided for without introducing any complication. The switch is in the form of a wooden cylinder with brass strips of various lengths on its circumference, which make reliable rubbing contact with stout flat springs, when the cylinder is rotated by an ordinary lever. Only four coils of about 1 ohm resistance each are employed; and by moving the switch lever the following nine changes can be made in the motor circuit, either rapidly, or slowly, step by step, as desired. The coils are denoted by A, B, C, D.

1. Circuit disconnected.
2. A, B, C, D in series.
3. A, B, C ,,
4. A, B ,,
5. A
6. A, B in parallel.
7. A, B, C ,,
8. A, B, C, D ,,
9. Resistance coils short-circuited.

It will thus be seen that not only are the lower resistances obtained without employing extra coils, but when the heaviest current is passing the heat generated is being spent upon the whole of the mass of the metal employed.

It is evident that whenever an intermediate gearing is employed between the armature shaft and the shaft upon which the work is required to be done, a considerable amount of power must be wasted, however well the gearing may be designed and made. It

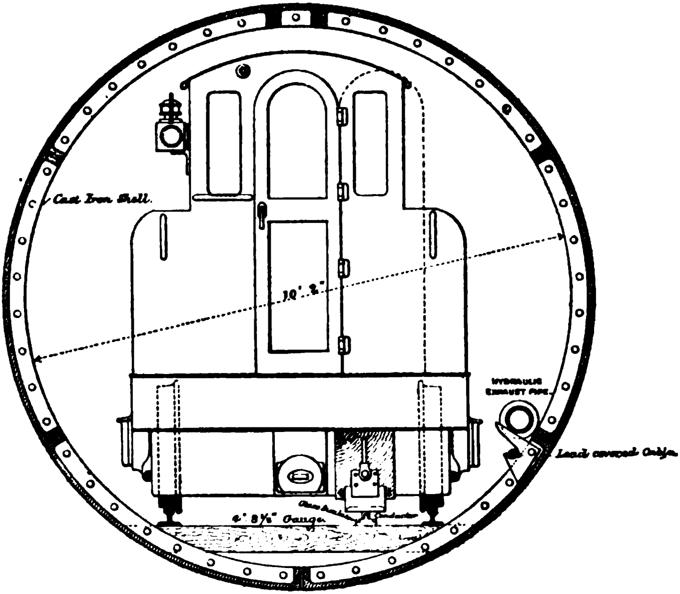
is therefore always advantageous to avoid such gearing and drive direct from the armature shaft, even though it may be necessary to employ a slightly less efficient motor for the purpose. As has been remarked, the speed at which the axles of an ordinary tram-car rotate is so low that it is hardly possible to drive direct in this case, but for electric railway work, where the speed may be considerably higher, the method has been successfully carried out. The first application was made by Messrs. Mather and Platt on the City and South London Railway, the electrical features of which present several points of interest. The up and the down lines run in separate tunnels throughout, the tunnels being constructed of cast-iron sections bolted together by internal flanges as illustrated in fig. 245, which shows a section through the tunnel and an end view of one of the locomotives. The rails are supported on wooden sleepers which fit and rest upon the sides of the tunnel as shown, the gauge being 4 feet 8½ inches. The conductor from which the current is taken is of channel steel supported on glass insulators and running throughout the line between the two rails, as indicated in the figure, its upper surface being about an inch below that of the rails. The motors are mounted on a separate car (which we refer to as the 'locomotive'), each locomotive drawing three passenger carriages. From the bottom of each locomotive three massive cast-iron trailers are hinged; these trailers, which are electrically connected, slide over the surface of the steel conductor and so collect the current. The conductor is composed of a special kind of mild steel which has a comparatively low specific resistance, the resistance of a mile of the conductor being a little more than a quarter of an ohm. The various lengths are connected with fishplates and bolts, but to ensure a good electrical connection copper strips are also employed, the ends of each strip being riveted to the ends of adjacent lengths of the conductor.

The generating station is placed at one end of the line, and instead of allowing the steel conductors to carry the whole of the current to the distant end, four 'feeders' are employed. These feeders are insulated copper cables with an external lead covering, the conductor consisting of 61 No. 14 S.W.G. wires stranded together; and they are connected to the steel conductor at

various points along the line. One of the feeders is seen to the right of fig. 245; it is supported by a bracket, which is bolted to the flange of one of the tunnel sections, this particular bracket also carrying the cast-iron exhaust pipe coming from the hydraulic lifts.

A longitudinal section of a locomotive with its two motors is given in fig. 246, where the three cast-iron trailers will be seen,

FIG. 245.



two on the right- and one on the left-hand side of the figure. The motors are series-wound, and they are joined in series with each other. The armatures are of the Gramme ring type, each having a resistance of 0·3ω, and the distinctive feature of the arrangement is that each axle of the locomotive also forms the shaft for one of the armatures, so that no gearing whatever is required. When the locomotive is running at its maximum speed of 25 miles per hour the armatures make 310 revolutions per minute, the two motors being

capable of developing about 100 horse-power under these circumstances. The field-magnets are of the Edison-Hopkinson type,

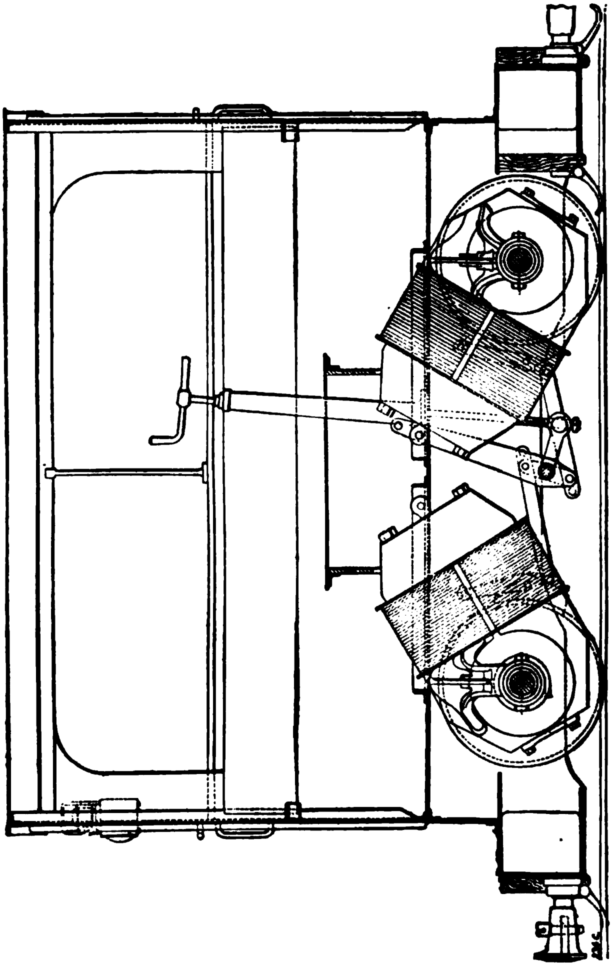


FIG. 245.

the resistance of the coils on each being 0·087$^{\omega}$. The yoke end of each field-magnet is supported from the framework of the loco-

motive by an arrangement of links which allows a certain amount of play, to correspond with the movements of the framework with respect to the axles. It is clear, however, that no up-and-down play can be allowed at the other end of the field-magnets, otherwise there would be risk of the pole-faces coming in contact with the armature. The field-magnet at the armature end is supported by bearings on the axle itself, so that the field-magnet simply rocks through a small angle about the axle or armature shaft as a centre, and the distance between the armature and pole-faces is kept constant.

The steel conductor is maintained at a pressure of about 500 volts above that of the earth, and the current passes from the trailers first to a fuse and main-switch, then to a second switch with a set of resistance coils, then through a reversing switch, and finally through the two motors in series, to earth by way of the wheels and rails. The reversing switch is for the purpose of reversing the direction of the current through the motors, and so reversing the direction in which the locomotive moves, while the resistance coils are placed in series with the motors when starting in order to avoid the passage of the too-heavy current which would otherwise flow before the motors had attained sufficient speed to develop any appreciable counter electro-motive force. By joining the two motors in series the pressure between the terminals of each becomes half that between the steel conductor and earth, when all the resistance is cut out of circuit; the current passing through one motor is always equal to that through the other, and varies of course with the speed at which the armatures are rotating.

Four Edison-Hopkinson dynamos are provided to generate the current for this line. The machines are compound-wound, the resistance of the armature of each being 0·017ω, of the shunt-coils 96ω, and of the series-coils 0·015ω. The machines are connected to a switch-board, to which the four feeders above referred to are also led, and the connections may be made so that the machines supply current to the feeders either separately or in parallel as may be desired, one terminal of every machine being always connected to earth. The output of each machine is 450 amperes at a pressure of 500 volts when running at 500 revolutions per minute.

The method of collecting the current from a third (insulated) rail, by means of trailers underneath the car, is perhaps the most satisfactory that can be devised, and is always employed when the circumstances permit. In the case of street tramway work, however, the conditions are not nearly so favourable as on the railway just described, where no other traffic passes over the road, and where the track, being all under cover, is kept comparatively dry. It is not permissible to lay a bare live conductor along a public street or road, on account of the other traffic, and even if, as in the case of the tramway first described, the conductor be laid in an underground channel, difficulties are apt to arise through stones and rubbish finding their way into the slot, while the insulation frequently falls to a very low value in wet and snowy weather. Crossings are also somewhat troublesome to satisfactorily arrange, and in any case the construction is expensive. For these reasons in most of the street tramway work which has been carried out, the current is collected from an overhead conductor, which is fixed at a uniform height throughout the entire length of the line. In the majority of cases a long arm is fixed on the roof of the tramcar, in such a manner that its upper end can move freely through a certain range in any direction (to enable any irregularities in the line to be followed), and the extreme upper end carries a metal shoe, which presses against the under side of the conductor. This shoe is connected through the arm and a suitable insulated cable to the switches and other apparatus employed, whence the current passes to the motor or motors, and thence to earth through the rails. The conductor from which the current is collected does not, as a rule, transmit the whole of the current to the distant end of the line, but is connected at intervals to feeders which supply it with current and maintain its pressure throughout at an approximately uniform value.

One disadvantage attending the running of motors in parallel circuit, supplied with current at a constant potential, as in the systems hitherto described, results from the fact that the current carried by the main leading wires is the sum of the current supplied to the whole of the motors. When the number is great, this main current becomes enormous, and the main conductors or feeders must be correspondingly massive to avoid

serious loss of power; and, of course, the greatest loss occurs at the time when it can least be permitted, viz. when the motors are demanding the maximum current. Many difficulties disappear in a system of distribution of power to motors which require to be supplied with a constant current, for all the machines can be joined in series, and the mains need only be of sufficient size to carry the current required by one machine, instead of the whole of them. But other difficulties arise, chiefly in connection with the means available for communicating the current to the motors, sufficiently great, in fact, to make the parallel system, on the whole, more practicable. In fact, although a number of promising systems have been tried, it can hardly be said that series working has yet been successfully accomplished for tramway or railway work. The parallel system is almost universally adopted, and the current to be carried by the mains is kept as low as possible by employing a comparatively high voltage at the motor terminals.

Undoubtedly the ideal arrangement is for each vehicle to be entirely self-contained, carrying not only its motor or motors, but also the immediate source of electrical power. For in such a system neither expense nor inconvenience is incurred by any alteration to the existing road, or by the erection of an overhead conductor, with its feeders, &c.; and a host of other attendant inconveniences are obviated. The only practical method of achieving this result is by the aid of secondary batteries. Each battery must consist of a sufficient number of cells to give the required potential difference at the motor terminals, and each cell must be of such a size or capacity as will enable it to supply a current of the maximum strength required. As the question of the loss in the mains does not now require to be considered, the necessity for a high potential difference disappears, and consequently a battery of, say, 50 cells, giving a pressure of about 100 volts, will in most cases suffice. With the reduction in pressure there must obviously be a proportional increase in current strength. Hence the cells, although comparatively few in number, must be very large and correspondingly heavy. Herein lies the first difficulty to be overcome, because although up to a certain point the increase of weight assists by increasing the adhesion between the

wheels and the rails, the minimum increase in weight with an effective secondary battery exceeds this limit, and therefore a considerable proportion of the energy expended is required to carry the battery itself. Efforts have been made to reduce the weight of the non-productive portion of the battery, as well as of the plates themselves; but hitherto this reduction has only been effected at the expense of mechanical strength and durability, and of electrical capacity. As the conditions are such as to subject the cells to considerable vibration, it is evident that unless they are mechanically strong their life will be but short; and a reduction in electrical capacity involves, of course, a frequent return to the generating station for re-charging. Unfortunately the ideal secondary cell for this class of work remains yet to be produced.

An important operation in connection with a dynamo machine is the determination of its commercial efficiency; that is, in the case of a generator, the ratio of the electrical power appearing in the external circuit and available for useful work, to the total mechanical power spent in driving the machine; and, in the case of a motor, the ratio of the useful mechanical power obtained on the armature shaft, to the total electrical power absorbed. The accurate measurement of the mechanical power in either case presents some difficulty. The usual method is to employ a transmission dynamometer, or a friction brake, to determine the horse-power expended or obtained, as the case may be; but it is not possible with either class of apparatus to be certain of obtaining any but an approximately correct result. The electrical power, on the other hand, can be measured with extreme accuracy, it being simply necessary to find the current strength in, and the potential difference at the extremities of, the external circuit of a generator; and the current passing through a motor, together with the potential difference at its terminals; the product of the two quantities in either case gives the power in watts.

If it were possible to arrange matters so that it would become essential to measure, by a mechanical process, only a small fraction of the total mechanical power given to a generator, say one-tenth (the other nine-tenths being measured electrically), then a much more accurate result might be obtained; for any error made in

measuring this fraction, when distributed over the whole amount, would have but one-tenth the value of that which would otherwise accrue. And, further, it is far easier to accurately determine the value of a small than of a fairly large amount of mechanical power.

An important departure, rendering such a method possible, has been made by Dr. Hopkinson. He takes two approximately equal machines, and, driving one as a generator, leads wires from it to the other, so connected that the current developed by the first machine drives the second as a motor. Now, the mechanical power appearing on the motor shaft is less than that spent on the generator, by an amount equal to the power absorbed by friction, and by the heating of the various conductors, armature cores, &c., in the two machines.

But the power which does appear on the motor-shaft might easily be employed to assist in driving the generator; and this is effected by the simple process of rigidly coupling the shafts of the two machines together; so that, then, the only mechanical power required to be supplied and measured is an amount equal to that just referred to as being wasted in the various parts of the two machines during the double conversion.

This fraction, thus supplied, is conveniently measured by a dynamometer of the Hefner-Alteneck type, which measures directly in pounds the difference between the pull on the tight and slack sides of the belt, that is, the actual pull causing the rotation of the pulley. This number, multiplied by the number of feet travelled by the belt per minute, gives the number of foot-pounds of work performed in one minute, which when divided by 33,000 gives us the horse-power supplied by the belt: since one horse-power is a rate of working equal to 33,000 foot-pounds per minute. With the particular dynamometer employed in one test made by Dr. Hopkinson, the pointer moved over one division of the scale for a pull of 2·705 lb. on the tight side of the belt in excess of that on the slack slide, and the radius of the pulley was such that one revolution corresponded to an advance of the belt through 3·63 feet; in this case, then, the work done per revolution was $2·705 \times 3·63$ foot-pounds for one scale-division.

From this it will be seen that if T represents the number of

scale divisions traversed by the pointer, and n the number of revolutions per minute, then the power applied

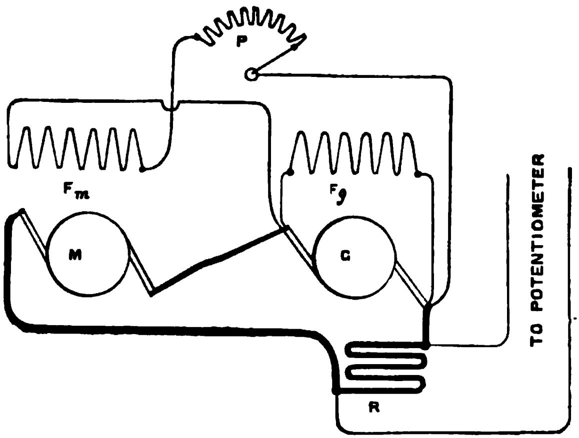
$$=\frac{2{\cdot}705 \times 3{\cdot}63}{33{,}000} \times n \times \mathrm{T}$$

$$=0{\cdot}000298 \times n \times \mathrm{T} \text{ horse-power.}$$

A number of experiments were made with the machines in the case under notice, and as they are interesting, the full results of one test, as furnished by the experimenter, are appended.

The electrical connections were made as in fig. 247, where G and F g represent the armature and field-magnet of the generator,

FIG. 247.



and M and Fm those of the motor, both the machines being shunt-wound. The heavy lines indicate the main connections between the two machines, and, in order to measure the current, a small accurately known resistance, R, is placed in the main circuit; to the extremities of R are connected wires leading from a potentiometer, by means of which, with a Clark standard cell, the potential difference between the ends of the resistance can be accurately measured.

This potential difference, divided by the resistance (which was in this case 0·0058 ohm), would give the current flowing through the main wire. The potential difference between the terminals

of the generator was measured by a Thomson graded voltmeter, previously standardised by a Clark cell.

Now, the two machines were exactly alike, and, consequently, if joined in opposition (as two shunt machines must be, when one is required to drive the other), and then driven at equal speeds, no current would flow from one armature to the other, for they would generate equal E.M.F.'s, or, in other words, the counter-electro-motive force of the motor would be equal to the electro-motive force of the generator. For this reason, it is necessary to weaken the strength of the motor field, in order to enable a current to be urged through its armature, and this was effected by placing a set of variable resistances, P, in series with the motor field-magnet coils; and, by altering this resistance, the current passing through the motor armature could be varied at pleasure. The motor field-magnet coils, together with P, form a shunt to the generator terminals; the motor armature thus receiving the whole of the current passing through R. Since the resistances of the two field-magnet circuits are known, the current in each can readily be calculated after the potential difference at the generator terminals has been measured.

The resistances of the armatures and field-magnet coils of the two machines were:—

Generator . .	Armature . .	0·009947	ohm.
	Field-magnets .	16·93	„
Motor . . .	Armature . .	0·009947	„
	Field-magnets .	16·44	„

1. The two dynamos were run with brushes removed and with the fields unexcited.

Scale reading = 21·6 divisions.
Revs. per minute = 808.
Horse-power = 5·2.

2. The two fields were separately excited, and the dynamos driven, still with the brushes off, when

Scale reading	= 30 divisions.
Revolutions	= 802.
Shunt current in field of generator	= 6·9 amperes.
„ „ „ motor .	= 6·7 „
Horse-power	= 7·169.

3. The connections were made as in fig. 247, and the following results were obtained :—

E.M.F. at terminals of generator	. =	110·12 volts.
Main current	. =	358 amperes.
Current through generator magnets	=	6·50 „
Current through motor magnets	. =	5·36 „
E.M.F. at terminals of motor .	. =	107·33 volts.
Speed of machines . .	. =	764 revs. per minute.
Power transmitted by belt .	. =	6602 watts = 8·850 h.-p.

Hence—

Total power given to generator	. =	42917 watts	=	57·53 h.-p.
Power lost in armature core .	. =	831 „	=	1·11 „
Power lost in generator magnets	. =	716 „	=	0·96 „
Power lost in generator armature	. =	1360 „	=	1·823 „

And therefore—

Commercial efficiency . .	. =	93·23 per cent.
Loss in core	. =	1·94 „
„ magnets . . .	. =	1·66 „
„ armature . . .	. =	3·17 „

Similarly for the motor—

Total power given to motor	. =	38886 watts	=	52·13 h.-p.
Power lost in internal friction of core	=	831 „	=	1·11 „
Power lost in motor magnets	. =	472 „	=	0·63 „
„ „ „ armature	. =	1275 „	=	1·70 „

And therefore—

Commercial efficiency of motor .	. =	93·37 per cent.
Loss in core	. =	2·14 „
„ magnets . . .	. =	1·22 „
„ armature . . .	. =	3·27 „

The loss due to friction of the bearings and one or two unimportant causes has then to be determined and deducted, to obtain the real commercial efficiency, which, after this deduction, was found to be : motor 92·6 per cent., and generator 92·5 per cent.

One disadvantage of the original method is that it is necessary to have two approximately similar machines in order to perform the test, and this is sometimes inconvenient. A number of modifications of the method have, however, been suggested, the measurement of even a fraction of the power mechanically being in some cases avoided, by obtaining the extra power representing the total waste by means of a small motor, and measuring the amount so supplied, electrically.

Any one of the alternate-current dynamos described in Chapter VIII. can be used as a motor; that is to say, its moving parts can be caused to rotate, and mechanical power thereby obtained on the armature or field-magnet shaft, as the case may be, by supplying power electrically by means of a suitable *alternating* current. Such machines have some important advantages, and some serious disadvantages. The chief advantages are, first, that the electrical power can better be supplied at a high potential difference with a comparatively small current, thus minimising the loss in the conducting leads; and, secondly, that the machine is perfectly self-regulating as regards speed, in spite of load variations, for it keeps perfect time with the generator. Its speed can readily be varied by varying the rate of alternation of the supply current, but this method is inconvenient for obtaining frequent speed alterations, and impracticable if the same generator is supplying more than one motor. Since so much distribution for lighting purposes is now being effected by alternating currents, the necessity for a perfectly satisfactory alternating motor is apparent, but up to the present no satisfactory motor is available for general use on such a circuit. The principal disadvantages are that an alternator cannot start itself, as can a direct-current motor, but has to be independently driven up to the speed of the generator; while if the load is made excessive the motor stops entirely, and has to be again started by some external means. The machine will, however, make great efforts to respond to any extra work thrown upon it, and to keep in synchronism with the generator, but will surely fail immediately the load is sufficient to drag it out of unison.

It is extremely inconvenient, and requires considerable power to start a large machine, whence any device to facilitate this is very welcome. Perhaps the most practical method yet devised is

that due to Mr. Mordey, who employs for the purpose the small machine used to excite the field-magnets. This, as seen in fig. 142, is coupled direct to the main-shaft, and, by means of a suitable switching arrangement, its current is at times made to pass through and charge a small secondary battery. When the machine is to be started the current from the battery is passed through the exciter for a minute or two, converting it into a motor, which puts the alternate current machine into rotation. As soon as synchronism between the alternate-current motor and the generator is obtained, the former is switched into circuit and continues to run as a motor.

Some extremely good results have been obtained with Mordey alternators when used as motors, proving them to be quite satisfactory for classes of work in which the speed does not require to be varied, or where frequent stoppages are not necessary.

From these motor properties of an alternator, results the very important fact that two independently driven alternating generators can be run in parallel, that is to say, their armatures can be connected in parallel so that the two machines can jointly supply power to the external curcuit. It is, however, essential that the two machines shall give the same rate of alternation, and also run co-phasally, that is to say, the maximum positive electromotive force, and also the maximum negative electro-motive force of the two machines must coincide in point of time. Then the resultant E.M.F. is the same as that of one, while the current, and also the power developed, will be doubled. Now the remarkable fact is, that the two machines will make great efforts to keep in phase, and will do so, even if the mechanical power supplied to one is increased or diminished within a reasonable limit. To explain this extremely important mutual action we may remember that the reaction between the armature and field-magnets of a *direct-current* dynamo when used as a generator is such as to tend to stop the rotation, and this tendency becomes stronger as the current in the armature increases, while a weakening of the current of course reduces the resistance to rotation. The speed might therefore be diminished by increasing the current flowing through the armature, by some external means ; while by inserting an opposing E.M.F. in circuit, and reducing the current, the speed

could be increased; and this variation in speed actually does take place in practice unless the engine is controlled by a good governor. Further, if the opposing E.M.F. exceeded that developed by the machine, the current through the armature would be reversed, and the machine would run as a motor.

Now, these effects can also be obtained with an alternate-current dynamo. That is to say, if the brief currents generated by it are increased in strength, the tendency will be for the machine to slow down, while if an opposing alternating E.M.F. acts in such a manner as to reduce these currents, the machine will quicken its speed; and it will run as a motor, doing work for the moment on the prime mover, if the opposing E.M.F. is sufficient to determine a current in the reverse direction.

Now when two alternators are driven independently, and coupled in parallel, and one begins to lag behind the other, the maximum E.M.F. of the leading machine occurs a moment earlier than that of the other, and consequently a heavy current flows from the leading to the lagging machine for a very brief interval of time. This current being opposite in direction to that which is then being generated by the lagging machine, tends to drive it as a motor and to accelerate its speed; or if the difference of E.M.F. is not sufficient to set up a reverse current, it weakens the existing one, with the effect of allowing the lagging machine to catch up, as already explained. On the other hand, the later occurring E.M.F. of the lagging machine will tend to increase the current in the leading one and consequently to pull it up. These reactions will commence immediately the alternators tend to get out of phase, and in well-designed machines the effect is so prompt and forcible that they run together perfectly, in spite of inequalities in the driving. It becomes very important, therefore, to decide what qualities and peculiarities a machine should possess to fit it for parallel working. Until recently it had been supposed that it was absolutely necessary for such a machine to have considerable self-induction, but even then the performance was admitted to be somewhat difficult and uncertain. Consequently, an armature without an iron core, and with few convolutions, was deemed to be undesirable; but these views have been somewhat shaken, and, to a great extent, entirely reversed, by the researches of Mr.

Mordey. That gentleman starts with the assumption that since the maintenance of synchronism depends upon the motor properties of the two alternators, the machine best fitted for parallel working must be one which possesses these properties to a high degree.

Consequently, the armature should have little resistance, and very little self-induction, and then the transfer of power by means of brief currents from one machine to the other, which serves to hasten or retard, as required, takes place much more suddenly, and the regulating action is much more prompt and forcible. Of course, the armature will have some self-induction and some resistance, but it is satisfactory to know that neither of these undesirable factors need be made abnormally high, merely for the sake of rendering parallel working practicable. It is probable, however, that there is a limit depending upon other conditions, (such as the rate of alternation,) below which it is inadvisable to reduce the self-induction, and that some definite relationship between self-induction and resistance should exist for any given case ; but, on the other hand, it is possible that this limit is very low, and that the working rule will be to make the two factors concerned as low as is practicable.

In the Mordey alternator, which has no iron in the armature, self-induction has a low value, so low, in fact, as to unfit the machine for parallel working if the old theory were correct. In order to support his views on the subject, the inventor made an exhaustive series of tests with two of these machines, each being similar in appearance to that depicted in fig. 142, but having an output of 50 horse-power, with a maximum E.M.F. of 2,000 volts, at a speed of 120 revolutions per minute. The details of one set of tests are given below. It should be noted that the machines were driven by two independent engines, not connected in any way, and provided with heavy fly-wheels ; each engine also drove a heavy set of countershafts, fitted with a number of belts, &c., so that the momentum was considerable.

1. The alternators were run up to full speed, and each excited to give 2,000 volts. When in phase they were switched in parallel without any external load, and without the insertion of any self-induction coils or resistance between them. They ran in parallel perfectly.

2. A considerable inductionless load was then put on, varied, and taken off. They ran equally well under all circumstances.

3. They were uncoupled, and then, the load being connected to the mains, they were suddenly and simultaneously switched in parallel and on to the mains with perfect success.

4. One alternator was excited to give 1,000 volts, the other giving 2,000 volts. They were then switched in parallel, and went into step perfectly, giving a terminal potential difference of about 1,500 volts. No extra self-induction or resistance was inserted in this or in any other case. A load was then put on without affecting their behaviour.

5. With one machine at 1,000 volts and the other at 2,000 volts, they were switched in parallel when out of phase, and instantly went into step. A large current appeared to pass between them for a fraction of a second, but not nearly long enough to enable it to be measured or to do any harm.

6. They were then left running in parallel while one was disconnected from the engine, by its belt being shifted from the fast to a loose pulley. It continued to run as a motor synchronously. A load of lamps was at the same time on the circuit.

7. The two machines were then uncoupled and excited up to 2,000 volts. They were then switched in parallel when out of phase and without any external load, and went into step instantly.

8. Whilst running as in 7, steam was suddenly and entirely shut off one engine. The alternators kept in step perfectly, one acting as a motor and driving the large engine and all the heavy countershafting and belts. It was impossible to tell, except by the top of the belt becoming tight instead of the bottom, which machine was the motor.

To find the power exerted by the alternator acting as a motor in 8, a direct current motor was put in its place, and the power required to drive the engine and shafting was found to be 20 horse-power.

The above results speak for themselves; but a word of explanation may be given with respect to No. 5. There is an E.M.F. in excess, of 500 volts, which would be competent to send an enormous current through the low resistance of the two arma-

tures, the low self-induction not being able to prevent it, even though it is only applied in the same direction for a very brief moment. No such dangerous current was observed, and there must evidently be some other cause to prevent or modify it. This rather interesting point has been very simply explained by Lord Kelvin, who points out that the effect of a sudden increase of the current at any instant through the two armatures, in the direction determined by the excess of E.M.F. of the more powerful machine, is to tend to increase the strength of the field of the weaker, and to decrease that of the stronger machine. So that although a strong current would be started round the two armatures, its effect would be to immediately strengthen the field of the 1,000-volt and oppose that of the 2,000-volt machine, until the E.M.F. developed by each would have nearly the same value, viz. 1,500 volts. This brief equalising current would pass twice for every complete alternation.

Almost all alternators of modern construction will run satisfactorily in parallel, but it may be noticed that the massive rotating parts of the Mordey machine assist in rendering it suitable for this class of work. In any such machine a considerable amount of mechanical inertia tends to prevent any decided variations of speed with the stroke of the engine, and it is also evident that a fairly high speed engine, or, at any rate, one in which the impulses on the crank shaft are frequent, is best suited for driving alternators which are run in parallel.

Although there can be little doubt that, in the hands of an experienced staff, an alternator having an armature whose resistance and self-induction are low is the most suitable for parallel working, it must be noted that a source of danger results from these low values. For example, should the field-magnet circuit of any one machine be accidentally broken while that machine is feeding a circuit in parallel with other machines, the faulty machine cannot then be driven as a motor, and so set up a counter-E.M.F. to prevent the passage of a heavy current; but the high pressure between the mains to which it is connected will immediately urge a heavy current through its armature. So suddenly does the current rise under such conditions that it becomes difficult to protect the

armature by any ordinary safety device, and there is a considerable risk not only of burning up the armature of the faulty machine, but also of seriously injuring those of the other machines feeding the mains. It is comparatively easy to protect an armature having considerable self-induction, as any ordinary fuse will act before the current can rise to a dangerous value in opposition to the self-induction.

CHAPTER XIII

TRANSFORMERS

WHEN it is desired to convey energy to a distance by means of electricity, either for the purpose of producing light or mechanical motion, the chief problem to be faced is, how to reduce to a minimum the waste of energy during the transmission. We have seen that when a wire is used to convey a current, the rate at which energy is lost in that wire can be measured by multiplying together the current strength in amperes and the difference of potential between the ends of the wire in volts, the result being the number of watts so expended. And since the potential difference is equal to the product of the resistance of the wire and the current flowing, the loss in watts may also be calculated as the product of the resistance and the *square* of the current strength. That is to say, in the first place the power expended in any part of a circuit is proportional to the resistance of that part. Suppose, for example, a dynamo were employed to furnish current to a number of lamps arranged in parallel, their joint resistance being 10 ohms; then if the resistance of the machine and leads or connecting wires were also 10 ohms, exactly as much power would be wasted, as would be usefully expended in the lamps, a state of affairs which manifestly could not be tolerated. If the resistance of the machine and leads were reduced to 1 ohm, then the power wasted would be one-tenth of that usefully employed, and so on.

The resistance of the combination to which power has to be supplied is, as a rule, extremely low; and when the lamps or motors are joined in parallel, the current carried by the mains is equal to the sum of that required by the whole of them. Consequently the

resistance of these mains must be kept extremely low, a small fraction of an ohm in fact, otherwise the proportion which the power wasted bears to the total quantity of power developed becomes excessive. To keep the resistance low, copper of high conductivity must always be employed, but the practical limit as regards sectional area is quickly reached on account of the high price of that metal.

Speaking generally, it may be said that transmission of energy to any considerable distance by electricity is not economical, if we depend upon the reduction of waste, merely by increasing the conductivity of the leads. Again stating the case as :

$$\text{Watts lost} = C^2R,$$

where R is the combined resistance of the leads and generator, we see that the only other way out of the difficulty is to reduce the current strength.

If this can be done the advantage is very decided ; for, by halving the current, the power wasted in any portion of the circuit is reduced to one-fourth. It may not, however, be evident at first sight, how with this reduced current the same amount of energy can be transmitted in an equal time.

Digressing for a moment, in order to introduce an analogy, the student will probably be aware that in transmitting power mechanically to a distance by a slowly moving cable or rope, it is imperative that the cable and the rest of the moving parts shall be very strong and massive, and consequently the power lost by friction, &c., becomes enormous. But the energy transmitted per minute is equal to the pull on the cable in pounds, multiplied by the distance in feet through which the cable moves in a minute ; so that, by increasing the velocity of the cable, the pull thereon can be reduced, and the strength and size of the cable and of the other moving parts can be correspondingly diminished, without reducing the amount of energy transmitted per minute. It is, in fact, possible to transmit enormous power by means of a light wire cable, if it travels with sufficient rapidity ; and the loss due to friction is obviously reduced with the reduction in size and weight of the moving parts. Even if it is essential for the power so transmitted to be taken for actual use from a slowly rotating shaft, it is still

economical to transmit it at a high velocity, and effect the necessary reduction in speed by suitable gearing.

Somewhat similarly, very great power can be conveyed electrically by a comparatively small current traversing a thin wire, if only the electric pressure or potential difference is sufficiently high; for the power in watts may be calculated as the product of these two factors (current strength and potential difference), and no difference in the amount is made by reducing one of them, if the other is increased in like proportion.

But unfortunately it rarely happens that electrical power can be utilised at a high pressure; for instance, 110 volts is usually the maximum pressure required by a set of incandescent lamps joined up in parallel, and consequently it becomes necessary to employ, if possible, some arrangement which shall perform the same function as does mechanical gearing in reducing speed. That is to say, we require some apparatus competent to receive electrical power in the form of a small current at a high potential difference, and again give out that power in the form of a heavy current, and at a correspondingly lower potential difference.

It is possible to construct such apparatus; and before proceeding further we may notice the two chief points to be borne in mind in designing it:—

1. The proportions of the parts must be so calculated that the reduction is effected in the desired ratio; or, the value of the resulting potential difference must be the required fraction of that applied to the apparatus.

2. The loss in power during the conversion must be kept as low as practicable; that is to say, the design must be such that the efficiency of the apparatus is high.

The conversion from a high to a lower potential is rendered possible by the fact, already fully explained, that by starting or stopping a current in a circuit, a brief current can be induced in a neighbouring wire. The circuit in which the original current is started or stopped is called the 'primary' circuit, while that in which the currents are induced is called the 'secondary' circuit.

In order to obtain the maximum effect, it is necessary to ensure that the secondary circuit is cut by as many as possible of the lines of force generated by the primary. The best method is

to wind the wire in two coils, and, placing them close together, to provide plenty of iron in the vicinity so as to make the primary lines of force extend out beyond the secondary coil. The iron should in fact form a closed magnetic circuit of low resistance, embracing both coils. The iron must be laminated, as in the case of a dynamo armature core, to avoid as far as possible the generation of eddy currents due to the rapid changes in the number and direction of the lines of force projected through the iron ; and the metal employed must also have a low coercive force, to minimise the loss by hysteresis. Instead of a primary current which merely rises and falls in strength, an alternating current, such as that developed by any one of the alternators described in Chapter VIII., may with advantage be and usually is employed.

Suppose the number of convolutions in the two coils to be equal ; then by sending a rapidly alternating current through the primary, an alternating current of about the same strength might be obtained in the secondary coil. Again, the secondary might consist of a great length of wire in many convolutions, thin wire being employed to enable it to be kept near to the primary. In this case the primary lines of force would cut the secondary circuit many times, and the induced E.M.F. would be much greater than that urging the current through the primary. But since the power obtained from the apparatus cannot be greater than or even equal to that given to it, a corresponding reduction in the other factor would be observed ; in other words, while the E.M.F. would be enormously increased, the current would be far feebler than that in the primary.

The student is probably familiar with a piece of apparatus known as an 'induction coil,' in which a rapidly interrupted heavy current of low E.M.F. is passed through a few turns of thick wire, adjacent to an enormous number of turns of finer wire. A bundle of thin varnished iron wire serves as a core, and a very feeble current of extremely high E.M.F. can be obtained in the secondary circuit. Such apparatus has proved of considerable value in experimental researches ; but it can hardly be said to have any very great importance from a commercial point of view.

We are far more concerned with the effects obtained by

proceeding in the reverse order, viz. by making the length of the primary much greater than that of the secondary.

Supposing, for instance, we use the fine wire coil of an ordinary induction coil as the primary, and the thick wire coil as the secondary; the former offers considerable resistance, and it will require a high E.M.F. to send an alternating current of even feeble strength through it. But on measuring the resulting current in the thick wire coil (now being used as the secondary), it will be found that while the E.M.F. is low, the current passing through this low resistance circuit is comparatively very heavy. It is a most important fact that by constructing such an induction coil so that nearly all the primary lines of force can effectively cut the secondary, the secondary E.M.F. can be made to bear nearly the same ratio to the primary E.M.F. that the number of convolutions in the one coil bears to the number in the other. Therefore, by making the resistance of the magnetic circuit very low, and also making the electrical resistance of the secondary circuit very low indeed, so that but little loss of power occurs in overcoming its resistance when a fairly heavy current flows, we can obtain at the terminals of the latter an alternating potential difference whose average value is, under all circumstances, practically equal to a definite fraction of the average of the alternating potential difference maintained at the primary terminals.

For instance, if the primary consists of 1,000 turns and the secondary of 10, and a current of 1 ampere passes through the primary coil while the potential difference is 500 volts, then the secondary current may be 100 amperes, and the induced E.M.F. rather less than 5 volts. This is the important case with which we have to deal, for it thus becomes possible to effect the much-desired object of transmitting electrical power at a high electrical pressure, and employing it at the required point at a lower pressure. A piece of apparatus which is capable of effecting this transformation from high to low pressure is called a 'transformer.'

The first transformer was constructed in 1831 by the immortal Faraday. The principles which he then discovered, of the remarkable action of a varying current upon an adjacent circuit, are of almost inconceivable importance; while the method of con-

structing his original transformer, which we shall briefly describe, was well abreast of the then existing practice.

Faraday procured a welded ring of soft round bar iron, $\frac{7}{8}$ inch thick, the external diameter of the ring being 6 inches. Round one part of this ring he wound about 72 feet of copper wire, $\frac{1}{20}$ inch in diameter, in three superposed helices, the distance round the ring thus covered being about 9 inches. The wire was bare, the first helix being insulated from the iron by a layer of calico; and twine was wound side by side with the wire, to prevent contact between adjacent convolutions. Then followed another layer of calico, over which was wound the second helix, insulated with twine similarly to the first, then another layer of calico followed by the third helix, the whole being covered by calico. The ends of each helix were brought out so that the three coils could be used separately, or conjointly, in series or in parallel.

On the other half of the ring a length of 60 feet of copper wire was wound in two equal helices, and insulated in precisely the same manner as before. These two coils were joined in series and connected to a galvanometer. The other three helices were also joined in series, and a battery connected up to them. The immediate effect of making this latter connection was seen in a violent deflection of the needle of the galvanometer placed in the 'secondary' circuit. The needle quickly came to rest at zero, but was deflected momentarily in the opposite direction on the battery being disconnected from the primary circuit.

The lines of force of the current in the primary coil were, of course, conducted round by the iron ring through the secondary coil, and the sudden cutting of this coil by them gave rise to the observed currents. As might be expected, however, a great many of the lines of force did not reach the secondary coil, and Faraday obtained a more violent deflection with the same primary current and shorter lengths of wire, by so arranging the two circuits that nearly all the lines of force generated were able to cut the secondary circuit. He disconnected the two helices which in the previous experiment were used as a secondary circuit, and in their place took two of the three superposed helices on the other half of the ring, joining them in series and to the galvanometer. The battery was then joined to the third helix, which formed the

primary circuit, and although the lengths of wire were so much shorter, rather better effects were obtained, because of the increase in the percentage of the lines of force usefully employed. Had Faraday supplied the primary circuit with a rapidly alternating current, he might have obtained an alternating current of half the strength, and of corresponding higher electro-motive force in the secondary circuit ; but his galvanometer would not have indicated the presence of this current if the reversals were too rapid to give the needle time enough to move with each pulsation. By using one helix for the secondary and two for the primary, the secondary current might have been of twice the strength of the primary.

We may repeat that a transformer should be so designed that it can effect the required reduction from high to low pressure with as little waste as possible. The wires of the two circuits should be so disposed with respect to each other that the greatest possible number of the primary current's lines of force cut the secondary circuit, while if iron is employed to assist in this direction, care must be taken that but little energy is lost in it by eddies and hysteresis.

To reduce the loss by eddies the iron must be laminated at right angles to the path which they tend to take, while it must be left, as far as possible, continuous in the direction of the lines themselves. Loss by hysteresis increases with the rapidity with which the current alternates, and with the density of the lines of force through, and the mass of, the iron, as well as the coercive force of the iron employed. These points must receive due consideration when the rate of alternation and the mass of the iron in the core are being decided upon. The maximum number of lines of force per square centimetre is rarely allowed to exceed 7,000 in the case of a transformer core. Attention must also be devoted to such points as economy of construction, efficiency of insulation, and the facilities for the escape of the heat which is the evidence of the inevitable loss during the conversion.

Perhaps the simplest type of practical transformer is a slight modification of Faraday's original one. An iron core might be entirely overwound with a few layers of thick insulated copper wire to form the secondary circuit, and a number of layers of thinner wire then wound over this to form the primary. Resistance is of

comparatively small importance in the primary coil, but it must be kept low in the other coil, because that carries a heavy current.

It might be thought that some advantage would be derived by interlacing the two coils so as to bring them into closer proximity, but this cannot be done in practice on account of the difficulty in maintaining effective insulation. The potential difference between even the extreme ends of the secondary coil is low, and little trouble is experienced in insulating this coil, but quite the reverse obtains with the primary. The wire-covering must not be too thick, otherwise the space occupied becomes great, but the utmost care must be taken to avoid bringing into proximity any convolutions separated from each other by a long length of wire, and therefore having a high potential difference between them. And as in practice wires connected to the secondary circuit are frequently led into places where they can be and are handled, every precaution must be taken to effectually insulate the secondary from the primary. For this reason the two coils are never interlaced, but are wound separately, with effective insulation between them.

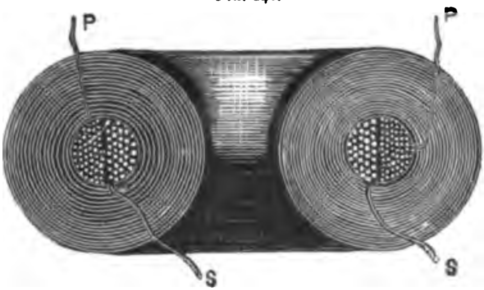
The simplest way of laminating the iron core of such a transformer is to build it up of thin iron wire, in exactly the same manner as the core of a Gramme ring. In fact, a Gramme ring armature having a large number of convolutions can be readily turned into a very fair transformer, by using two or three equidistant sections joined in parallel for the secondary coil, and the remainder in series for the primary. Transformers are sometimes so constructed in sections, but the usual way is to wind the wires spirally in two continuous coils.

The rapid reversals of magnetisation which take place, quickly heat the iron core, however well it is laminated. This heat must escape, and since the iron is enveloped by copper, the heat must be imparted to the copper before it can reach the external air. This heating of the conductor is very undesirable, and for this and several other reasons it is preferable to place the iron outside instead of inside the wire, the position of the iron being quite immaterial, provided it can act effectively in leading the lines of force through the desired paths.

In fig. 248 is illustrated one method of constructing such a transformer. Its external appearance is that of a massive ring of

small internal diameter, and in the figure is shown a section taken through a diameter, at right angles to the plane of the ring. The primary and secondary coils are each wound in a single coil, and lie close together concentrically. They are wrapped round with an insulating material, and over this is wound spirally an enormous quantity of soft iron wire. The inner coil of thick wire, S S, is the secondary, while the primary coil of thinner wire, P P, lies outside it, and it will be observed that the depth of the layer of iron wire is about equal to the diameter of the compound coil of copper wire. Such a transformer gives fairly good results, for nearly all the primary lines of force extend out to the massive iron shell, and in so doing cut the secondary. But it is an extremely tedious and expensive piece of apparatus to make on a large scale, on account of the slow process of winding the enormous length of iron wire. Further, if a fault should occur, and faults *will* occur, it becomes necessary to remove the whole of the iron wire before the coils can be got at, to remedy the fault.

FIG. 248.



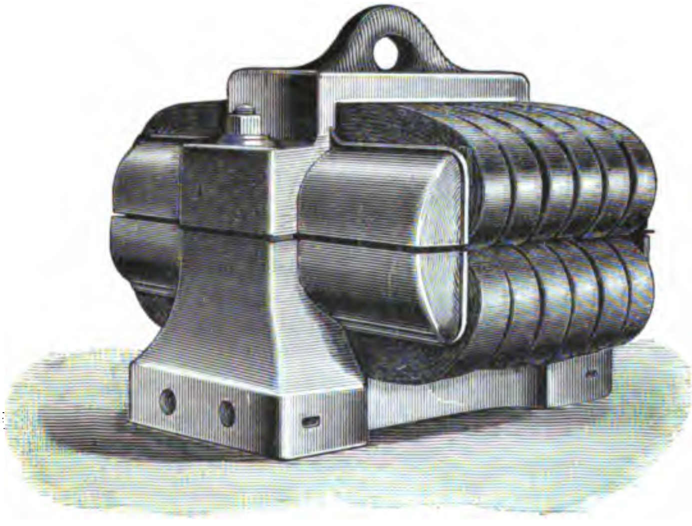
Consequently large transformers are not made in the manner illustrated, although in most cases the principle is the same. The apparatus usually consists of two coils of wire, nearly oblong in shape, lying side by side, with an easily fixed, and easily removable laminated iron covering.

About forty years ago a first-rate method of constructing a large transformer was patented by C. F. Varley, which may be regarded as a combination of the two types mentioned. He took a bundle of iron wires of approximately equal lengths, and over this bundle wound the primary and secondary coils. These coils were placed in the middle of the bundle, and extended along it for a distance equal to one-third of its length, so that the iron wires protruded from each end to a distance equal to the length of the

coils. The ends of the iron wires were then bent round over the coils, so as to meet and overlap each other, thus completely encasing the coils with iron, except at one place through which the connecting wires were led.

But the necessity for large transformers did not then exist, and the method was scarcely at all employed. It is, however, somewhat extensively used at the present time, because of the ease with which the iron shell can be fixed or removed. The highest practical development of this type is seen in the Ferranti trans-

FIG. 249.



former, which is now doing heavy work in London. A general view of a Ferranti transformer, designed to receive about fifteen electrical horse-power at a high potential difference, and yield a large percentage thereof at a lower potential difference, is given in fig. 249. A quantity of hoop-iron, divided into six bundles, forms the base upon which the essential parts of the apparatus are built up. Over the middle of this is wound a layer of thick insulated wire or strip, to form the secondary coil. The finer wire, to form the primary coil, is wound on a convenient frame in sections,

which are slipped over the secondary, and carefully insulated from it and from the iron. The protruding ends of the hoop-iron bundles are then bent over the coils, half at the top and half at the bottom, as shown in the figure, their ends meeting and overlapping for a short distance. The whole is then placed in a cast-iron framework, made in two pieces and securely bolted together, the portions of the coils not enveloped by the laminated iron being covered, mainly for purposes of protection, by large shields, which are cast with the frames.

The lamination is, of course, not so effective as if iron wires were employed, or as if the iron bands were placed edge-on to the direction of the lines of force; but the construction is very easy, and the spaces left between the bundles of hoop-iron greatly facilitate the escape of the heat developed.

The magnetic circuit of many transformers is built up of a number of flat plates of sheet-iron, placed so that the plane of the sheet shall be as far as possible parallel to the direction in which the lines of force are thrust through the iron. They are usually insulated by a thin coating of varnish, or by paper, or sometimes calico, and the devices by which such plates may be cheaply made and placed in position are very numerous. As they differ but little in principle, we need select only two patterns for description.

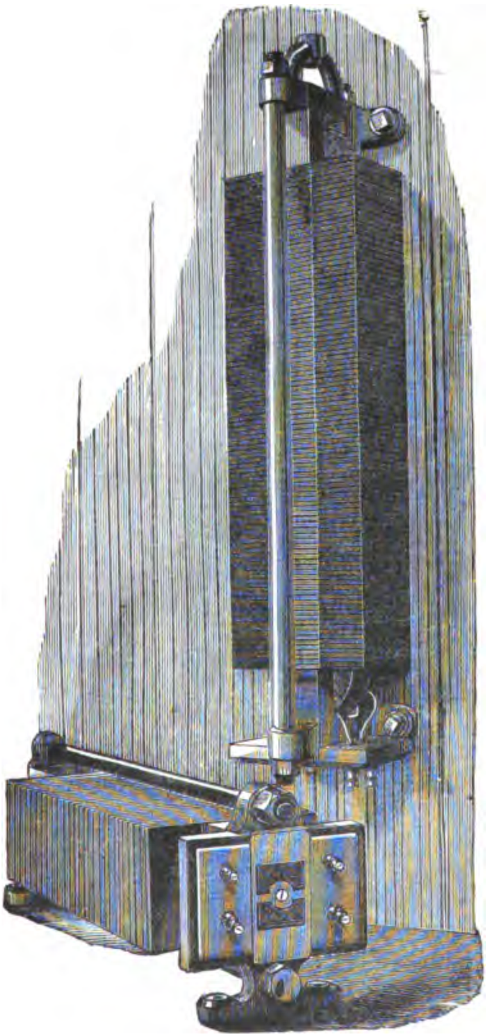
Two general views of the Mordey type of transformer, without an external casing, are given in fig. 250. The thin iron plates are oblong stampings, and an oblong strip is stamped out of the middle of each, exactly equal in length to the breadth of the original plate. When this strip is placed across the middle of the plate its ends just reach to the edges thereof, leaving two rectangular openings, one on either side of the strip, which are subsequently occupied by the wire. The primary and secondary coils are wound separately on a frame of such a shape that each coil consists of two parallel straight portions, with rounded ends, the section being rectangular and of such size that the two coils when placed one over the other just fill the openings in the plates previously referred to. The larger stampings are slipped one by one over the coils, alternating with the narrower strips which are threaded through the coils, the coils, with the exception of their

rounded ends, being in this way completely encased in iron. When the requisite number of plates have been placed in position, they are clamped tightly together between two cast-iron end-plates, held by bolts and nuts, as shown in the figure. The apparatus can either be fixed to the wall, suspended from the roof, or screwed down to the floor, as may be convenient.

There is a small air-space between the ends of the plates, whence the surface available for dissipation of heat is considerable.

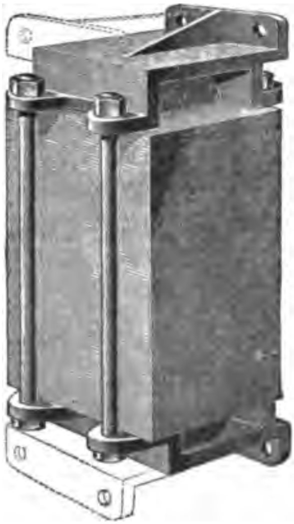
On the end face of the transformer shown in fig. 250 four terminals are shown, two for the primary coil and two for the secondary. But in the more recent apparatus the secondary coil is wound in two equal sections, the ends of each section being

FIG. 250.



brought out to separate terminals, so that each transformer has two primary terminals and four secondary terminals. The two sections of the secondary coil may then be connected either in series, or in parallel, or even employed to feed a 'three-wire system,' as will be explained in the concluding chapter. One size of this type of transformer, for example, is designed to be connected across primary mains which are maintained at a potential difference of 2,000 volts, and when the secondary coils are joined in parallel they give a heavy current at a pressure of 50 volts; while when they are connected in series they furnish a current of half the strength at a potential difference of 100 volts.

FIG. 251.



Except for experimental work, transformers are usually enclosed in cast-iron cases, and, as an additional precaution, they are frequently further protected by an earth-connected galvanized-iron wire cage.

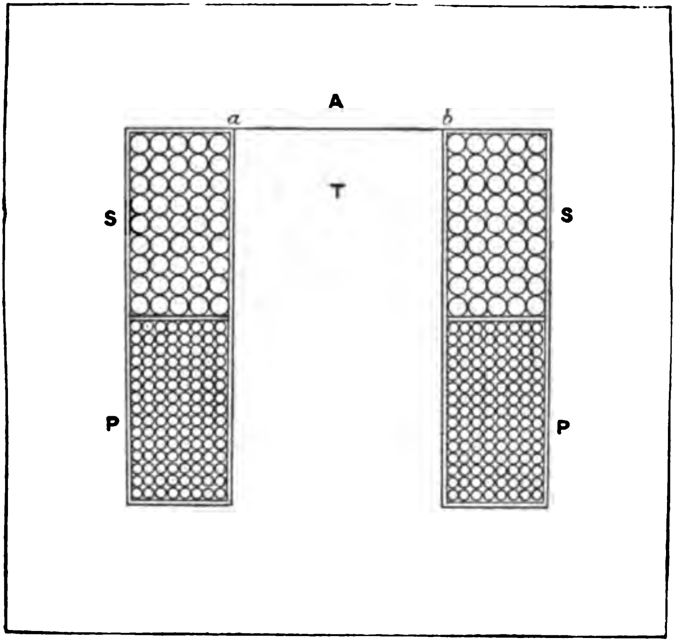
In fig. 251 is illustrated the transformer designed and constructed by Mr. J. G. Statter. A section is given in fig. 252.

The iron stampings (fig. 252) are nearly square in shape, and two oblong pieces are stamped out of each to form the spaces in which the wire is placed. S S is the thick secondary coil, while P P is the primary, and these two coils are wound to the proper shape on a suitable mould or frame, and placed one over the other as indicated in the figure. The strip T of each stamping is divided from the plate at one end, along the line *a b*. In building up the transformer the tongue T thus formed is bent at right angles to the plate, which can then be slipped over the coils, and the tongue restored to its normal position. A large number of these thin plates being similarly slipped on, the wire is surrounded on all sides by iron.

Two strong cast-iron end-plates, and four bolts, hold the thin

plates in position, and form a protective covering to the otherwise exposed ends of the coils. They are also provided with flanges and bolt-holes for fixing the transformer in any required position. The end-plates are frequently fitted with an extra flange, as indicated by the dotted lines, to which is screwed a wooden case, with a glass front, providing accommodation for a safety fuse, and

FIG. 252.



also a double-pole switch, by means of which both wires leading to the primary coil can be simultaneously disconnected.

These transformers are made in a variety of sizes, but the most frequent are those capable of transforming down from 2,000 volts to 100 volts, 2,000 to 50, 1,000 to 100, and 1,000 to 50.

Transformers have been put to a novel and interesting use by Professor Elihu Thomson, who employs them for the purpose of

obtaining the very heavy currents which are necessary in his method of electric welding. This method consists in placing the two pieces of metal required to be welded end to end, and subjecting them to moderate pressure against each other. A very heavy current is then passed from one to the other, and as they make imperfect contact at their opposing surfaces, considerable resistance is there offered to the passage of the current, and a very intense heat is consequently developed at the point where it is required to make the weld. If the current is sufficiently strong, the opposing surfaces get white hot, and being pressed together they unite perfectly, bulging out, however, round the edges. It is necessary that the surfaces should be perfectly clean, and a flux, the composition of which depends upon the nature of the metals to be welded, is usually employed to prevent the oxidation of the surfaces and so render the weld more perfect. In the case of iron, a little borax is sprinkled over the ends of the rods.

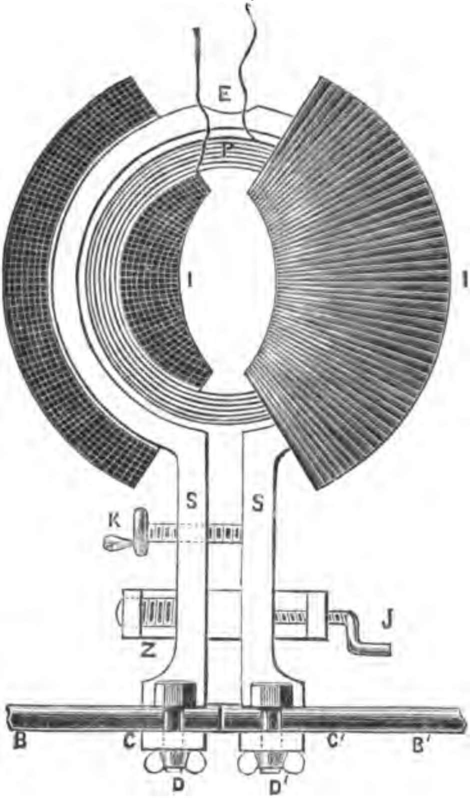
But in order to sufficiently raise the temperature of thick rods of metal, enormous currents are required; for instance, a current of about 20,000 amperes would be required to weld a steel rod seven-eighths of an inch thick. In such a case the resistance of the current generator must be extremely small, otherwise the power absorbed in it would amount to many horse-power.

Secondary batteries might be employed for the smaller currents, but the most economical method is to generate an alternating current by means of a dynamo, at a fairly high E.M.F., and, reducing this to a lower E.M.F. by means of a transformer, obtain at the same time an increase in the current strength.

Various types of transformer have been employed for the purpose, one form being illustrated by the diagram in fig. 253. The primary coil, P, is composed of a number of turns of wire, wound in a circular coil; the secondary consists of a single massive copper strip, S S, bent into a circular form, and placed concentrically with the primary coil. Over the two coils is wound a quantity of iron wire, I I, in two masses, space being left between them on one side, for the passage of the wires leading to the primary coil, and on the other side, to bring out the massive straight bars forming the ends of the primary coil. The bars can be held open by means of the screw at K; their extremities being provided with

massive clamps, C C′, in which the pieces to be welded, B B′, are fixed. A spiral spring at Z presses the ends together, the pressure being regulated by means of the screw at J. There are several modifications of this apparatus for performing special classes of work, the principle, however, being in nearly all cases the one illustrated. More elaborate mechanical contrivances are frequently introduced for clamping the rods or tubes to be welded, and for regulating the pressure at the junction.

FIG. 253.



For ordinary work a current of 12,000 amperes is the maximum required, and in such a case the power is usually supplied to the primary at an E.M.F. of about 600 volts, the current being twenty amperes. A certain amount of this power is, of course, lost during the conversion; but a current of 12,000 amperes at an E.M.F. of nearly one volt can be obtained in the secondary circuit.

It is important to observe the reason for most of the heat being developed at the proper point. When the current is started in the secondary circuit, the resistance at the junction is far greater than the resistance of the whole of the remainder of the circuit; consequently the fall of potential there is comparatively very great,

that is, nearly the whole of the power appearing in the secondary is expended in overcoming the resistance at the opposing surfaces. These surfaces get hot, and being pressed together, they then make much better contact. The rise in temperature, however, considerably increases the resistance, and consequently the expenditure of power at this point is still proportionally great. The ease with which the heat can be confined to any particular locality constitutes one great advantage of the method. It is usual to quickly remove the welded pieces, and hammer the joint into shape on an anvil. The clamps make contact with a large surface, to avoid, as far as possible, the introduction of resistance, and they are so designed that the removal of the welded rods can be speedily effected.

There are two distinct methods of distributing power to a number of transformers, each of which has several important advantages to recommend it. First, the whole of the transformers may be joined in series, and a constant current sent through the whole of the primary coils. Secondly, they may all be connected in parallel between two main leads, which are kept at a constant potential difference, so that the difference of potential between the ends of all the primary coils is always the same.

The former is in some cases the more economical as regards main conductors, for the maximum current in them is only equal to that supplied to one transformer, and is the same when the maximum amount of work is being done as it is during any smaller demand. But a generator is required which will supply a constant (alternating) current, under all variations in the external circuit; and as such a machine does not at present exist, it becomes necessary to employ somewhat unsatisfactory hand regulating devices. Difficulties also arise with regard to the regulation in the secondary circuit.

The E.M.F. appearing in the secondary circuit varies directly with the strength of the primary current. It also depends upon the number of convolutions in the two coils, and the goodness of the magnetic circuit (that is, upon the mutual induction between the two coils), and also upon the rate of alternation; but as these quantities are usually fixed for any given transformer, we may say that the secondary E.M.F. varies simply with the current passing through the primary. The strength of the secondary current, how-

ever, will depend largely upon the resistance of the secondary circuit. Now in the case of a series transformer the primary current is kept constant, therefore the secondary E.M.F. is also constant, and manifestly we cannot maintain a constant potential difference at the secondary terminals, nor a constant secondary current, if the secondary resistance is in any way varied. Were the lamps joined up in parallel, therefore, it would be necessary, on cutting any one of them out, to substitute an equivalent resistance, which would of course be wasteful.

The mutual induction might be, and in fact has been, varied to suit changing conditions by providing an adjustable core; but this is also unsatisfactory.

A better plan is to join either arc or low-resistance incandescent lamps in series, and on removing one to replace it by a resistance coil, or, preferably, by a choking coil, that is to say, by a coil of wire provided with an iron core, and having considerable self-induction. Its apparent resistance should be equal to that of the lamp which it replaces.

In such a series transformer the number of turns in the secondary is, as a rule, equal to that in the primary, through which a current of 10 amperes is maintained.

But if the transformers are joined up in parallel, and a constant (alternating) potential difference is maintained between the mains across which their primary coils are connected, then an almost constant potential difference can be obtained in the secondary circuit, even though the resistance therein be considerably varied. The lamps can be joined in parallel, and if the transformer is properly designed it will be almost self-regulating; for the current passing through the primary, and therefore also the secondary E.M.F., will be almost proportional to the number of lamps thrown in circuit, that is, inversely proportional to the secondary resistance.

The reactions which cause this self-regulation are very important and interesting, and in order to better understand them the student may, with advantage, again read some of the remarks concerning self-induction, &c., in Chapter VII.

On considering the construction of either of the parallel transformers just described, it will be apparent that since the primary

coil consists of many convolutions, and is almost completely surrounded by a mass of soft iron, the conditions for enormous self-induction exist. In fact, supposing the secondary circuit for the moment to be absent, or disconnected, the self-induction is so great that an appreciable interval of time elapses, before a current in the primary rises to its full value, although the potential difference may be high. And if the potential difference be rapidly alternated, it will not remain constant in one direction long enough to allow any appreciable current to be forced through the coil. But supposing the secondary circuit is completed through a rather low resistance, so that it is possible for fairly strong currents to flow therein, then the conditions are altered. For directly a current *commences* to flow in the primary coil, the lines of force springing out from the wire, not only cut the neighbouring convolutions of that coil tending to give the effect known as self-induction, but also cut, and set up an opposite current in the secondary. The lines of force due to this secondary current re-act on the primary coil (see fig. 119) in just the opposite sense to its own lines of force, tending thereby to neutralise the self-inductive effect, and allowing the primary current to rise rapidly. Although the length of the secondary is less than that of the primary, the current flowing through it is much greater, which may be expressed by saying that the lines of force per unit of length are more numerous. Consequently, if the secondary resistance is very low, allowing strong currents to flow, this reaction is competent to reduce the apparent primary self-induction to a comparatively small value.

If then a number of lamps are joined in parallel in the secondary circuit, an increase in the number switched in means an increase in the secondary current, and a corresponding increase in its reaction on the primary, which allows a greater current strength to be attained therein ; while when all the lamps are cut out, the primary self-induction is sufficient to throttle or choke back the current almost entirely. On account of these remarkable self-regulating properties, nearly all distribution is performed by means of transformers joined in parallel. Although the size of the mains is somewhat larger than on the other system, the advantages far more than counterbalance this objection, and it is a comparatively

easy matter to obtain an alternating generator which can maintain a constant potential difference.

By regarding the action of the primary upon the secondary coil in the manner developed in Chapter VII., it will be at once apparent that the currents in the two coils are always in opposite phase; in fact, in an ordinary transformer, the secondary negative maximum occurs almost simultaneously with the primary positive maximum, and *vice versâ*.

In all cases great care must be taken to avoid a leakage from the primary to the secondary circuit, for a potential difference of several thousand volts, such as is frequently employed, might cause a fatal accident in the actual lamp circuit should any other point in the primary circuit be making earth at the same time. Many safety devices have been suggested, one being the interposition of an earth-connected metal sheathing between the two coils; so that any breakdown in the insulation would cause a current to flow to earth sufficiently strong to melt a safety fuse in the primary, and thus disconnect that particular transformer without interfering with others working in parallel with it.

Such a fuse would also act if by any means the apparatus got short-circuited; and something of the kind is essential, for otherwise not only would all the transformers be deprived of power, but the heavy current which would result might cause serious damage.

The metal sheathing referred to should be insulated with extreme care, and must not form a closed metallic circuit round the inner coil, otherwise powerful eddy currents would be induced in it.

Another safety device is due to Major Cardew. Between two horizontal stout brass plates is placed a strip of aluminium foil, one end of which is free while the other is attached to the lower brass plate, which is in its turn connected to earth. The upper plate is connected to the secondary coil, so that should this plate assume a much higher potential than the earth, the foil would be raised by electrostatic attraction, and, touching the upper plate, would short-circuit the secondary coil. This would allow a sufficiently strong current to pass through the primary to melt a fuse placed in the circuit, and in that way cut out the transformer. If the primary circuit is making earth at any point, and any leakage occurs between the primary and the secondary, the upper

brass plate is immediately raised to a sufficiently high potential to attract the foil, and cut out the transformer in the manner described. It cannot, however, be too strongly insisted upon that any such earth connection is a serious source of danger unless the earth connection is good and absolutely reliable—that is to say, unless there is no appreciable resistance between the earth and the point required to be connected thereto. We have, for example, met with more than one instance where the earth, although good in wet weather, became ineffective in dry weather, the resistance to earth being so great that in the event of even a slight leak the conditions were established for serious shock to be obtained.

Independently of any earthing devices to guard against leakage from the primary to the secondary circuit, fuses should be inserted in the two primary as well as in the two secondary leads. These fuses should be placed as close as possible to the transformer, and the two in the primary circuit should be sufficiently long to avoid any risk of the high pressure setting up and maintaining an arc between the fuse terminals after the fuse itself has been destroyed.

Hitherto when comparing alternating currents with direct currents, we have considered only the simple average value of the former. But it is important to note that in cases where it is required to compare alternating and direct currents with respect to their capabilities of performing work, this simple average value of an alternating current does not enable us to directly effect the comparison. For example, if a current varies according to the sine law, its average value is 0·637 of its maximum value—that is to say, if its maximum strength is one ampere, its average strength is 0·637 ampere. But if a steady current of 0·637 ampere is maintained through an incandescent lamp, the lamp is less brilliantly lighted than by an alternating current whose maximum reaches one ampere, and whose average value is therefore 0·637 ampere, which clearly shows that more work is being done in the latter than in the former case. This arises from the fact that the work performed at any instant varies as the *square* of the current strength at that instant, and the average of the square of the current at every instant is greater than the square of its average value. In fact, in the case of a current varying according to the

sine law and with a maximum value of one ampere, if the current strength at every instant be squared, the average value of these squares will be 0·5, the square root of which is 0·707. Consequently such a current is equivalent, as regards heating or the performance of other work, to a steady current of 0·707 ampere. Precisely the same argument applies with respect to electro-motive force, and to avoid misunderstanding it is usual to refer to this 'square root of the mean square' value of an alternating current or pressure as the 'virtual' amperes or volts, as the case may be.

It may be noted, for example, that a Siemens dynamometer indicates virtual amperes, since the force of attraction is at any moment proportional to the square of the current strength; while for a similar reason an electrostatic voltmeter indicates virtual volts. Similarly, a hot-wire voltmeter indicates virtual volts, because the heat developed in the wire is at every instant proportional to the square of the current strength, and this square varies with the square of the pressure.

In the case of any circuit, or portion thereof, having no self-induction, the virtual volts multiplied by the virtual amperes will give a correct value for the power being expended therein, because the current rises and falls simultaneously with the pressure; but the presence of self-induction causes the current to lag behind the electro-motive force, so that while at one moment both current and pressure may be acting in the same direction, at the next moment the current will be positive and the electro-motive force negative, or *vice versâ*. Now work is actually done in the circuit only during the time that the current and pressure are in the same direction, and in order to obtain the true value of the work done in a circuit having self-induction a correcting factor must be applied. This factor must reduce the product of the virtual amperes and virtual volts in a degree which increases with the lag of the current behind the pressure, and it can be shown that the required reduction is effected if the product of virtual amperes and volts be multiplied by the 'cosine of the angle of lag.' For instance, if the angle of lag were 10° (the cosine of which is 0·985), and the virtual amperes and volts 10 and 50 respectively, the power expended would be $10 \times 50 \times 0{\cdot}985 = 492{\cdot}5$ watts. In the extreme case, which can never be perfectly attained in practice, where the current

lags 90° behind the electro-motive force, no power would be expended in the circuit, because the cosine of 90° is 0. This ideal state of affairs would result from the fact that the current and pressure would be in opposite directions during precisely the same length of time that they were in the same direction, and just as much work would be returned by the inductive circuit in the former interval as would be expended in the latter interval.

The matter may be rendered easier of conception by the consideration of a number of mechanical analogies which will readily suggest themselves. For example, if a spiral spring be alternately compressed and extended, work is done during the compression; but a considerable portion of it is given back again during the extension, and the work so given back might be utilised to considerably reduce the total amount of work done if the agent employed were capable of again receiving it and storing it up, as can be done electrically.

It should be remembered that when a transformer, with its secondary circuit disconnected, is joined across the primary mains, and a fairly strong current flows through its primary coil, this current does not necessarily represent the rate at which power is being wasted in the primary circuit, because the high self-induction of the primary coil causes the current to lag behind the pressure. Hence also we see the advantage of making the self-induction of a choking coil high, in order to make the angle of lag as great as possible, and thereby to reduce the power wasted in the coil.

CHAPTER XIV

SECONDARY BATTERIES

It was stated when describing the simple cell, that its great drawback, so far as concerned its general utility, was its comparatively rapid polarisation, a phenomenon which consisted in, or rather resulted from, the development of a film of hydrogen gas upon the surface of the negative plate. This hydrogen being electro-positive to zinc, a counter electro-motive force was set up, and the conditions for the flow of a counter current thereby determined. But chemical reactions, similar to those which take place inside a battery cell, may be repeated in any part of the circuit by causing the current to pass through suitably arranged metals and liquids. The usual method of performing electro-chemical experiments is to attach metallic or carbon plates to the ends of the wires connected to the poles of the battery, and then dip these plates in a vessel containing the liquid upon which the current is to act. Thus, if the ends of two copper wires terminating in copper plates, are connected to the copper and zinc poles respectively of the battery, and placed in a vessel containing acidulated water, then the passage of a current will cause a quantity of that water to be decomposed, and the constituent gases, oxygen and hydrogen, to be released from their state of combination. The hydrogen will accumulate on the surface of the plate connected with the zinc pole, while the oxygen will combine with the other plate, just as it happened with the zinc plate in the simple cell. If, however, we substitute a strip of platinum for the copper plate connected with the copper pole of the battery, the liberated oxygen will not enter into any combination, but remain in a gaseous state, a large portion of it rising into the air, and the remainder adhering to the surface of the platinum or entering its pores and becoming in a measure occluded or absorbed

by it. The absence of chemical combination between the platinum and oxygen is due to the weak chemical affinity subsisting between those two simple substances. By observing proper precautions the two gases may be collected separately, the apparatus for the purpose of producing the decomposition and collecting the products being called a voltameter. A serviceable form of this class of instrument consists of three glass tubes, all in communication at their lower extremities, the middle one being taller than the others and terminating at the top in a small reservoir, to keep the two outer tubes supplied with solution, and to prevent the liquid overflowing when driven from them. Platinum wires are fused through the glass and terminate inside in strips of platinum foil, which form the electrodes, their outer extremities being connected to terminals fixed on a wooden base. Taps are ground into the upper portions of the outer tubes, affording facilities for the escape, when required, of the confined gases. On sending a current through the solution, the decomposition of the water takes place, the oxygen collecting in one tube and the hydrogen in the other, according to the direction of the current. The water displaced by the gases collecting in the tubes, shows readily that the quantity of hydrogen evolved is always twice that of the oxygen, in consequence of the fact that the gases exist in that proportion when combined to form water. If the platinum electrodes are now disconnected from the battery and joined up to a galvanometer, it will be seen that a current of electricity is produced by the voltameter, but that the direction of this counter or secondary current is opposite to that of the battery or primary current which caused the separation of the gases.

A series of voltameters is, to all intents and purposes, a Grove's gas battery, each cell of which consists of two tubes, closed at the top and dipping into a glass vessel. A platinum wire is fused into the upper portion of each tube, and carries a long strip of platinum foil. Assuming the current from the battery to pass through the series, oxygen will be collected on one set of electrodes, while hydrogen will be collected on the other set. If, after the current has been allowed to flow for some little time, the terminals are connected to a galvanometer, a current will be observed to flow, opposite in direction to the charging or primary current, and this reverse or secondary current, which is, after all, only the effect

hitherto referred to as polarisation, taking place under favourable circumstances, will continue to flow so long as the gases remain in contact with the platinum. As a matter of fact, we have set up a secondary battery with 'plates' of hydrogen and oxygen, and in maintaining the current, the hydrogen in one set of tubes combines with the oxygen of the water, forming new water molecules, while the equivalent hydrogen eventually released from the water, combines with the oxygen in the other set of tubes. This action results, therefore, in the formation of water, as shown by the very simple equation :—

$$H_2 + OH_2 + O = OH_2 + OH_2 = 2\,OH_2.$$

We see here, then, an exact counterpart of the action that takes place in a primary cell, resulting there in the polarisation of the cell and the tendency to generate so-called secondary currents. The difference of potential or electro-motive force between the free hydrogen and oxygen is 1·47 volt, and that is a measure of the force of chemical combination between these gases, whence it follows that, in order to overcome this force of combination, and therefore to decompose the water, we must employ for each such secondary cell an electro-motive force exceeding 1·47 volt.

Cells in which the energy of chemical change can be thus stored up, to be given out again when required in the form of an electric current, are frequently called electrical accumulators or electrical storage cells. It is not, however, electricity which is stored or accumulated, but rather a quantity of the active constituents of a cell, and it is the subsequent chemical action between these constituents which causes the flow of electricity. It is therefore preferable to style them secondary cells. This will be more apparent when it is remembered that a primary cell can have a current sent through it in the opposite direction to that in which the current generated by it would flow, and this current will cause the usual negative plate to be more or less dissolved and the positive plate replenished, setting up the conditions necessary to the re-establishment of a primary current. If, for example, we suppose a powerful reverse current to be urged through a Daniell cell in which the copper sulphate has been exhausted, the copper plate will be partially dissolved and copper sulphate reformed, while

zinc will be deposited upon what remains of the zinc plate. The cell is then able to again generate a current of its own.

Although the gas battery is exceedingly interesting, as a secondary generator it is not a practical piece of apparatus, for, on account of the limited quantity of gas which can be accumulated and rendered available, it is only able to maintain a current for a very short space of time. Many experiments have therefore been performed to determine the best liquid and electrodes (the metal plates immersed in the liquid), for a practical form of secondary battery. The most assiduous worker in this field was Planté, and the result of his labours was the discovery that lead electrodes in a solution of sulphuric acid give the best results. He found that a large portion of the oxygen combined with the plate at which it was released, forming an insoluble compound, which when opposed to a clean metallic lead plate developed a potential difference of from 2 to 2·5 volts. In Planté's method the lead plates employed were comparatively very large with a view to increasing the amount of active material and reducing as far as possible the resistance of the cell. They were first laid one over the other, but separated by strips of non-conducting material, and then rolled up together in a kind of double spiral. In this way an enormous surface was presented to the liquid. On sending a primary battery current through the cell, from plate to plate, the water was decomposed, the oxygen combining with the metal at the positive electrode to form peroxide of lead, PbO_2, while the hydrogen was precipitated upon the negative electrode in the gaseous form, without in any way attacking the metal. The cell so acted upon became a secondary cell in which the negative electrode acted as the positive plate, being a sheet of lead with a partial film of hydrogen gas, the other plate or positive electrode with its film of insoluble lead peroxide behaving as the negative plate. It will thus be seen that the pole of the secondary cell which is connected to the positive pole of the primary generator, whether a battery or a dynamo machine, becomes the positive pole of the secondary, the other extremity becoming perforce the negative pole.

On permitting the reverse or secondary current to flow, what remained of the hydrogen was oxidised and converted into water,

some of the subjacent lead being also oxidised at the expense of the water. On the other hand, the peroxide on the other plate was deoxidised or reduced to metallic lead, in a 'spongy' form. These experiments can be very easily performed by sending for a short time a current from three or four good-sized Daniell cells through a vessel containing two pieces of sheet lead immersed in sulphuric acid solution. The piece connected to the copper pole of the battery will, after the passage of the current, be discoloured, and assume a brownish tint, owing to the partial oxidation of the surface of the metal, while the piece connected to the zinc pole will assume a greyish metallic colour. The amount of chemical change taking place during these reactions is, owing to the limited extent of the surfaces, very small, and consequently when these lead strips are connected direct to a low resistance galvanometer, they will yield a current of but brief duration. The amount can, however, be increased by augmenting the lead surfaces, and by prolonging the time during which the primary battery is joined to the lead strips. It was found by Planté that after sending the primary current through the secondary cell for some time, and thereby nearly covering the surface of the positive electrode with a film of the peroxide, the oxygen released from the water, instead of continuing to combine with the lead, formed into bubbles and escaped into the air. There was thus for a given metallic surface a limit to the amount of peroxide that could be formed. In order to increase this amount, the cell was allowed to send a current in the reverse direction to the charging current, until it had discharged itself almost completely. The consequence was that the spongy lead plate, acting as the positive of an ordinary cell, combined with oxygen, and thereby became oxidised, while the other plate which had already absorbed a quantity of oxygen became deoxidised, and was in its turn reduced to the condition of spongy lead, with a proportionally increased surface. A fresh direct or 'charging' current on being sent through the cell again oxidised this extended lead surface and reduced once more the negative surface to the spongy lead state. These reversing operations being continued for some time, both positive and negative surfaces were eventually very considerably increased by the plates being rendered more or less porous, one of them, however,

being always in a state of oxidation. After a few days a period of rest was allowed to intervene between the reversals, and during these periods, the 'formation' of the plates was developed in a remarkable way by 'local action.' The lead peroxide on the charged positive plate did not form a continuous impervious coating over the plate, but allowed the solution to pass between its particles and come into contact with the metallic lead. The peroxide being at places also in direct contact with the lead, a simple voltaic pair was thus established, with the lead for the positive and the peroxide for the negative elements. The acid attacked the lead and formed lead sulphate ($PbSO_4$), which is but a poor conductor of electricity; some of the peroxide was at the same time reduced to a lower form of oxide, probably the monoxide, PbO. The amount of lead actually affected was thus increased and the porosity of the plate gradually made more and more complete. In a somewhat similar way the surface of the negative plate was also attacked, and a film of lead sulphate formed, more especially during the interval of rest following a discharge, because there was then a quantity of lead oxide distributed over the surface of the plate. Lead being positive to its oxides, the pure metal would be attacked during the local action that would ensue, and be more or less sulphated. The development of the lead sulphate on the plates would not, however, increase the 'charge' given to the cell; in fact, if the cell were left idle for a considerable time, it would be eventually discharged by the gradual conversion of the plates into lead sulphate. During the forming process, however, the development of the sulphate would be advantageous, as it has the effect of increasing the amount of lead surface available for subsequent charging. It will thus be seen that the process of forming the plates might have been continued until the whole became porous by its conversion into spongy lead, but there is a practical limit to the action, for if pursued too far, the plate would fall to pieces, simply on account of its inability to mechanically support itself.

The plates having been once formed, no further reversal is effected excepting for the purpose of discharging the cell to perform useful work.

This method of forming the plate is, however, very tedious

and very expensive, and many efforts have been made to overcome the objection. One method is to subject the lead to a nitro-sulphuric acid solution which rapidly eats into the metal and, rendering it more or less spongy or porous, increases its surface correspondingly. Another method is to fill a vessel with molten lead, and, when it is on the point of solidification, to make an opening in the bottom of the vessel, and allow such of the metal as remains in the liquid state to flow out, leaving behind it a spongy porous mass. This is cut up into plates of the required dimensions.

One of the best forms of lead plate battery is the Epstein. Each plate consists of a single corrugated lead casting, the cross section of a portion of one of these plates being illustrated on a considerably enlarged scale in fig. 254. The effect of these corrugations is to present to the solution five times the surface that would be obtained with a smooth plate of the same external dimensions. The castings are 'boiled' in a weak nitric acid solution prior to 'forming,' in order to still further increase the surface, the subsequent treatment being exclusively electrical. The plates are immersed in a sulphuric acid solution, and the passage of the charging and discharging currents causes the usual spongy formation, as shown in fig. 254, but the lead peroxide and spongy lead thus formed adhere very strongly to the solid metal, and the consequent durability is one of the chief advantages of this type of cell as compared with other types to be presently described. It should further be noticed that the continuity of the solid metal involves a correspondingly low and uniform resistance. In fig. 255 is illustrated one of the cells specially designed for heavy work and rough usage. The plates are in this case contained in an ebonite cell. It will be seen that there are four plates electrically connected. These form the negative plate, and between them are three thicker plates which are likewise electrically connected, and which together form the positive

FIG. 254.

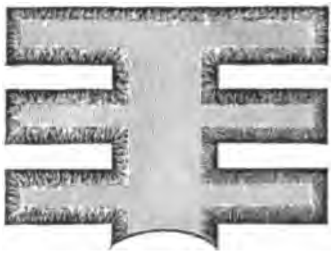
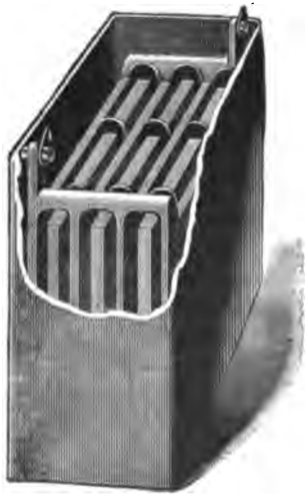


plate. Such a 7-plate cell has a total-weight of about 52 lbs., and measures 8¾ in. long by 5¼ in. wide and 11 in. high. The charging current required is 25 to 40 amperes, and the discharging current can vary up to as much as 50 amperes; but, as will be seen from what will be said later on, the capacity of the cell, or the amount of electricity which can be obtained from it, falls somewhat considerably as the rate at which the current is discharged, is increased. It may, however, be noticed that an occasional heavy current may be obtained from these cells far in excess of the normal maximum current without the risk of any permanent injury ensuing.

FIG. 255.



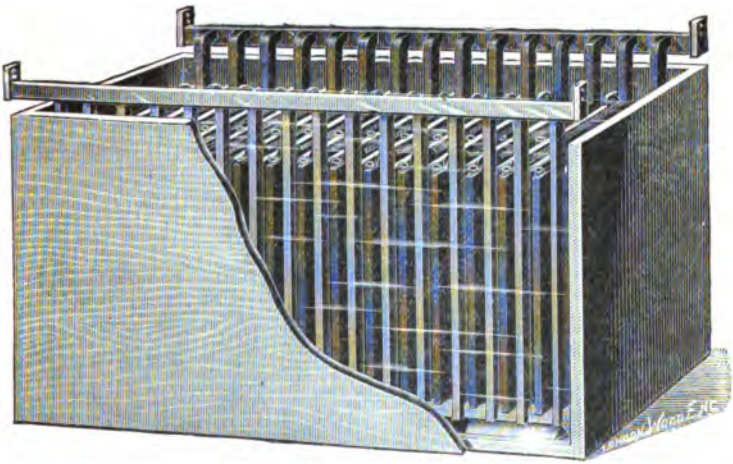
The cells are made in various sizes and shapes to suit the various classes of work which they may be called upon to perform. One size containing (fig. 256) 31 plates weighs, with the acid, 980 lbs.; it measures 15 in. long by 32½ in. wide and 19 in. high. The charging current is 390 amperes, and the cell can discharge for 10 hours at 195 amperes, for 6 hours at 300 amperes, for 4 hours at 390 amperes, or for 2 hours at 675 amperes.

Lead plates pure and simple, when formed by an electrical process, are often known as Planté plates, but the type of cell more generally employed is that which is based upon the idea of Faure, which was to coat the plates with a paste of lead oxide and acid, and so to more easily facilitate the extension of the lead surface. A mixture of sulphuric acid and minium or red lead (Pb_3O_4) was made, which resulted in the formation of a paste of lead sulphate ($PbSO_4$). This was applied to both the positive and negative plates, that on the plate in connection with the positive pole of the dynamo or primary battery, being, by the charging current, converted into peroxide of lead, by the absorption of oxygen, while the paste on the other plate

was reduced more or less completely to the condition of spongy lead. In this way the active surface speedily becomes considerable, and it will be seen that the great value of Faure's invention is to minimise the amount of energy required to be expended electrically in forming the plates.

It is now the general practice with 'pasted' plates to employ a paste of litharge (PbO) and acid, for the plate connected to the negative pole, the employment of this oxide involving a smaller expenditure of energy in deoxidising than would be involved in the reduction of a higher oxide. In all cases, however, whether

FIG. 256.

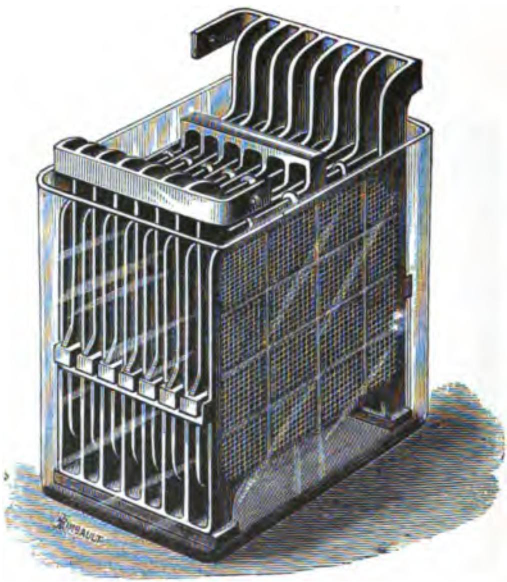


lead plates or pasted plates are employed, the ultimate result of the initial charging is the same, viz. the conversion of a portion of the positive plate into peroxide, and of the negative plate into spongy lead.

The Faure pastes adhere very feebly to the lead plate, and many devices have been attempted to secure better adhesion. One of the earliest plans was to score or scratch the lead surface. Then it was indented, the indentations developing subsequently into perforations. The paste, on being squeezed into the holes, certainly kept its position much better than when

simply smeared over the roughened surface of the lead, but the quantity of paste exposed to the liquid was reduced. Eventually, leaden grids were cast containing sufficient metal to bear the weight of the plate, the holes being square and somewhat pyramidal, that is, smaller in the middle of the plate than on the surfaces, so as to prevent, as far as possible, the peroxide from falling out. In this form of plate, when properly treated, the pellets gradually get harder, until ultimately it is difficult to detach

FIG. 257.



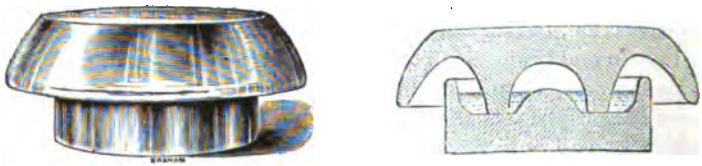
them. An illustration of the so-called L or 1888 type of cell, manufactured by the Electrical Power Storage Co., is given in fig. 257. A number of grids of lead are filled with the paste, the number of grids varying with the size of the cell, but always with one negative plate in excess of the number of positive plates. The negative and positive plates are placed alternately, so that by employing a negative plate in excess of the number of positives, the two outer plates are negative, and there is a negative facing

each side of every positive. The negative plates are all connected together, and so also are the positive, the object of having a large number of plates being, of course, to increase the capacity of the cell, and to reduce its internal resistance, without resorting to the use of inconveniently large plates. Each grid measures about $8\frac{1}{2} \times 9\frac{1}{2}$ inches, and is $\frac{3}{16}$ inch thick, the weight being about 5 lbs.

The lead grids are provided with massive lugs for the purpose of connection, the lugs of the positive plates being all melted or cast on to one leaden strip or band, the lugs of the negative plates being similarly secured to another strip. The distance between two adjacent plates is about a quarter of an inch, which is usually sufficient to allow pieces of the plates or paste that may become detached to fall to the bottom of the cell. Bent strips or forks of ebonite, celluloid, or other suitable material, are placed between the plates to keep them apart and prevent internal contact. The negative plates in each cell are also held rigidly together by means of two stout strips of lead melted on to solid extensions from the lower edges, two others being also secured to the sides of the plates about half-way up. These connecting strips, one of which is shown at the left-hand side of the figure, serve as a further means of keeping the negative plates in position. The bottom strips rest on slabs or strips of paraffined or varnished wood, so as to support them at a height of about $1\frac{1}{2}$ inch above the bottom ot the containing cell, affording thereby plenty of room for any scales or pellets that may fall to the bottom to lie clear of the plates. Lugs cast on to the edges of the positive plates rest in small ebonite shoes, which are supported by the side-strips of lead attached to the negative plates. The positives are also connected together across the top by the substantial lead strip shown a little to the right of the middle of the upper edges of the plates. The con necting strip to be seen on the left is melted on to projections rom the corners of the plates, consequently they can be readily lifted out of the cell, without necessitating the removal of the negative plates. The containing vessels are best made of stout glass, an opportunity being thus afforded for the proper inspection of the cell, without taking it to pieces or removing the plates. The upper portion of the outer surface of the glass vessel should be coated with wax, vaseline, or some such material, to prevent

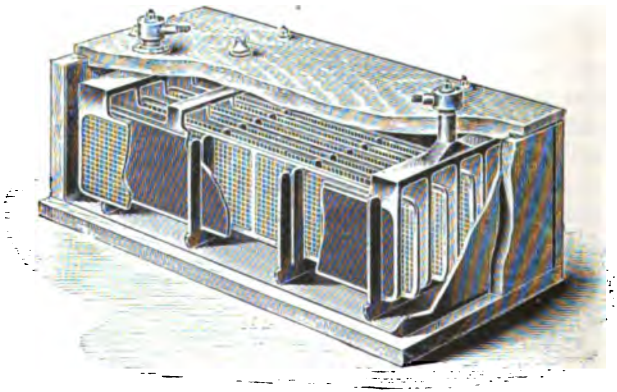
'creeping' and the partial short-circuiting of the cells by means of the continuous film of moisture that would otherwise condense over the whole of the external surface. To further ensure good insulation, the cell should be placed on a varnished wooden tray (containing a quantity of sawdust) and supported by insulators of

FIG. 258.



the so-called mushroom pattern illustrated in fig. 258. The channel in the lower cup contains, as shown in the sectional view of the insulator, a quantity of resin oil or of some other non-evaporating oil, in which the upper cup, coated with shellac varnish, rests. The cells should not be quite in contact, but

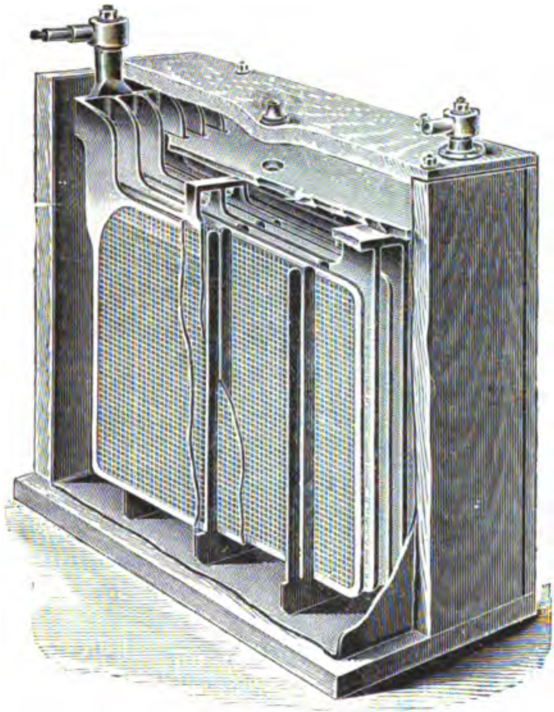
FIG. 259.



fairly close together, and the connections made either by 'burning' or melting the lead strips of adjacent cells together, or by clamping them firmly in a special form of terminal. When the latter method is resorted to, the connection should be painted over with shellac varnish, paraffin wax, or some such impervious

material, to protect the brass against the corrosive action of the acid, which, when the cell is well charged, sprays up considerably. The positive pole of one cell is, of course, connected to the negative of the next, and so on. The positive connecting strips are usually painted red for the purpose of distinction. All leading wires should be as short and of as low resistance as possible, so as

FIG. 260.



to avoid unnecessary waste of energy in overcoming the resistance of the connections. The resistance of secondary cells is very low, the current obtained from them is usually heavy, and it often happens that the connections offer more resistance than do the cells themselves.

Fig. 259 illustrates a very useful form of cell specially con-

structed for train lighting. It is enclosed, like other classes of cells intended to be carried in a vehicle, in a teak box lined with lead, and contains, to suit different requirements, either nine or fifteen plates separated by celluloid forks. Sometimes, in order to further reduce the risk of contact and short-circuiting between adjacent plates, thin perforated celluloid sheets are interposed between them. Connection between adjacent cells is of course made externally, rods attached to the connecting strips passing through the covers for the purpose. Connecting rings fit on to these rods, through slots in which wedges are driven to secure good electrical contact, the rings of adjacent cells being joined together by stout wires or rods. Cells are also made specially for tramcar driving, these being, for very obvious reasons, constructed as light as they practically can be, and enclosed in teak or ebonite boxes. They are made in four different sizes containing as many different numbers of plates. Fig. 260 illustrates the method of enclosing the large L type plates in lead-lined teak boxes, for purposes where a heavy current is required. The peculiar shape of the forks in this case and in that illustrated in fig. 259 should be noticed.

FIG. 261.

Another and very important type of the Electrical Power Storage Co.'s cell is that illustrated in fig. 261, and known as the K or high discharge type. The positive plates are considerably thicker than the negative, and are connected together and supported by two lead bars of large dimensions which rest on insulating

saddle-pieces placed on the upper edges of the negative plates. These two bars are joined by an angular piece of lead, so that the connection from cell to cell is made at the middle of each end of the containing vessel instead of at the sides, as in fig. 257.

The negative plates stand on prolongations or feet at each of the bottom corners of each plate, the plates being joined together at the foot by lead bars of similar dimensions or area to those joining the positive plates, while at the top corners the negative plates have a projection at the side, which is also utilised for joining the plates together by bars of lead. At one end of the bars joining the feet of the negative plates a cross-bar and lug, in the form of an inverted tee-piece, forms the connecting lug, which leaves the containing vessel at the middle of one side and in such position as will enable it to meet the angular connecting lug from the positive plates of the next cell.

FIG. 262.

The separation between the respective plates is obtained in the usual manner by ebonite forks. There are small niches in the top edge of the positive plates in which the forks are intended to rest.

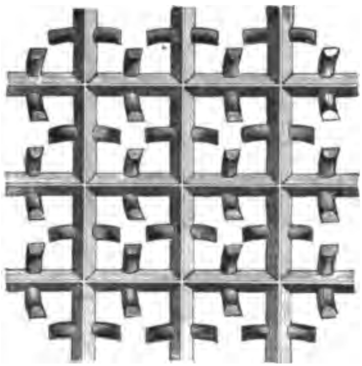
In fig. 262 is shown, full size, a portion of one of the positive plates of these cells. It consists of a massive lead casting, with a number of thin horizontal ridges on both faces. These ridges are inclined upwards and are packed with the usual minium paste. A portion of one of the negative grids is illustrated in fig. 263. This grid consists of a comparatively light lead casting with a number of small projecting prongs, the function of which is to keep the small litharge pellets in position.

When the discharge rate from a secondary cell is excessive, the active material expands, and there is therefore with cells of the L type a tendency to dislodge it. This, as will be seen presently, results in the distortion of the plates and the disintegration or splitting of the pellets, which consequently fall out of the grid. As the risk of this action taking place with the K plate is obviously

very much smaller, they may be worked with safety at a correspondingly higher rate, plate for plate, the surface area in the two cases being the same.

The normal maximum discharge rate of these cells is at the rate of 8 amperes per peroxide or positive plate, a rate which is about twice as great as that permitted with plates of the L type, and even this high rate may be considerably exceeded for short periods, say of half an hour. This latter feature is an important advantage in certain cases, such as one might expect to arise when some portion of the generating plant breaks down when under load. Cells of the K type have only about half the number of plates, and occupy only about half the space required for the L type for a given output, while the weight is about three-fifths. The prime cost is also reduced in about the same proportion. When, however, the K type is discharging twice as fast as the L type with the same number of plates, it can only maintain its current for a much shorter period of time; but if batteries of the two types, both having the same number of plates, are discharged at about the normal rate for the L type, the two will be able to maintain their respective currents for nearly the same period. As secondary batteries are rarely required to maintain their heavy discharge for many hours successively, the advantage of the newer type, although considerable, is perhaps less than might at first sight appear; for although its discharge-rate is high, its efficiency is somewhat lower than that of the L plate. On the other hand, it gives promise of greater durability.

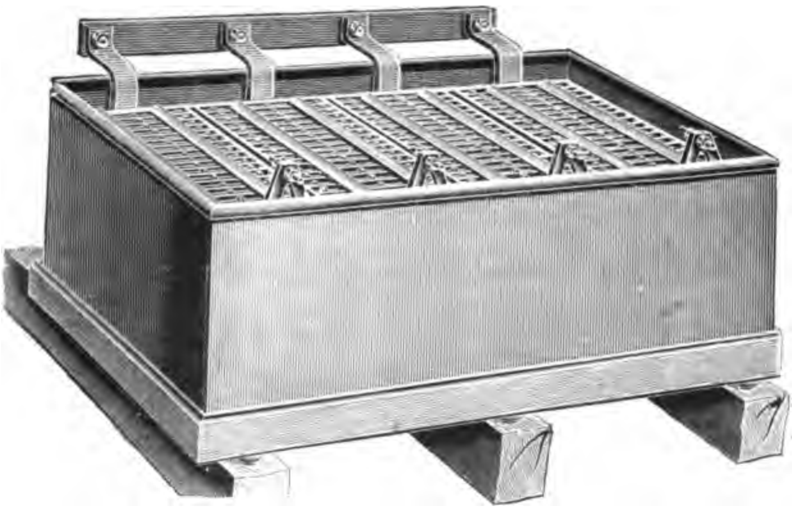
FIG. 263.



The maximum working rate of the largest cell of the K type is 135 amperes, but for Central Station and other similar heavy work a higher rate is required. To meet such demands, batteries have been joined in parallel. There are two ways of effecting this.

One is to join the terminals of two batteries together, but some difficulty is experienced in keeping the two at a common potential difference; and where this is not done, trouble may very easily arise. The other method is still less satisfactory, and consists in joining the cells in parallel in pairs, and then joining the various pairs in series. It is evident that it is almost impossible to maintain each pair of cells at a common potential (indeed, it is difficult to ensure this in the case of the different pairs of plates in any one cell), and when this is not done, a wasteful expenditure of

FIG. 264.



energy must ensue. To overcome these difficulties, a type of cell known as the Central Station type is manufactured. It is a development of the K type, and one of these cells is illustrated in fig. 264, which practically consists of four sets, each set composed of 33 K plates. The four ordinary negative terminal strips are shown connected to a common terminal bar, while the four positive angular terminal pieces are provided with the usual bolts for connection to the next cell. A cell of the size illustrated requires a maximum charging current of 540 amperes, while it can, in discharging, maintain for one hour a current of

1,200 amperes, for three hours a current of 600 amperes, for five hours a current of 450 amperes, or for seven hours a current of 350 amperes. It will be seen that the slower the rate of discharge, the greater is the amount of energy which is given back. Similarly, the most economical rate of charging is from one-half to two-thirds of the maximum rate, because, among other things, at this higher rate the oxygen is released faster than it can be absorbed.

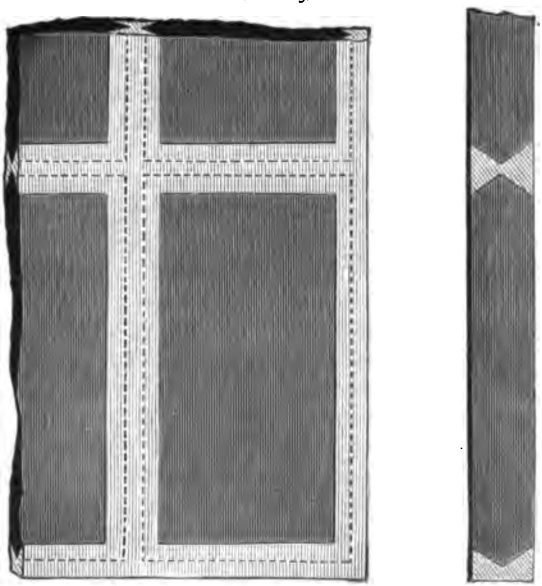
A few details concerning some of these various types of cells will doubtless prove of service. In the subjoined table, L indicates cells of the 1888 type intended for general lighting, C for railway carriage lighting, T for tramcar propulsion, K the high discharge type, and Q a class of cell serviceable for small work.

Description of Cell		Acid 1·170 sp. g. for each Cell	Working Rate		Capacity	Approximate External Dimensions				Weight of Cell complete with acid
No. of Plates	Material of Box		Charge Amperes	Discharge Amperes	Ampere-Hours	Length	Width	Height	Height over all	
		lbs.				ins.	ins.	ins.	ins.	lbs.
L 15	Teak	35	25 to 30	1 to 30	330	9½	13½	18¼	20½	143
	Glass	48	25 to 30	1 to 30	330	9⅝	11¾	13¾	15¾	128
L 31	Teak	70	50 to 60	1 to 60	660	19¼	13¾	18¼	20⅜	286
	Glass	96	50 to 60	1 to 60	660	18½	12	13¾	15⅝	265
K 15	Teak	40	30 to 58	1 to 58	196	10	12¼	17¼	19½	178
	Glass	44	30 to 58	1 to 58	196	9⅝	11¼	13¼	16½	161
K 33	Teak	84	66 to 135	1 to 135	448	20¼	12¾	17¾	20	381
	Glass	90	66 to 135	1 to 135	448	19⅜	11⅜	13½	16¾	348
C 9	Teak	8·4	6 to 8	1 to 8	72	6	13⅝	6¼	7⅝	38
C 15	Teak	14	12 to 14	1 to 14	136	9½	14	6¾	8¼	62
T 15	Teak	14	24 to 28	1 to 30	95	8¼	8¾	11⅜	13⅜	52
	Ebonite	14	24 to 28	1 to 30	95	8	7¾	11	12¼	42
T 23	Teak	22	38 to 42	1 to 50	145	13¼	8¼	11⅜	13¾	79
	Ebonite	22	38 to 42	1 to 50	145	12¼	7¾	11	12¾	66
Q 3	Teak	·9	·5 to 1·3	1·3	7	2	5½	7⅜	7¾	5½
Q 21	Teak	6·5	10 to 13	13	70	9¼	5¼	7⅛	8	28

There is another type of cell known as the Lithanode, in which the active material, containing between 80 and 90 per cent. of lead peroxide, is obtained from the monoxide of lead made into a paste with a solution which causes the material to set into a more or less rigid mass. Fig. 265 gives a section and elevation of a portion of one of these plates, in making which the slabs of

lithanode are arranged in a casting mould, the molten metal being run in to form the grid and complete the plate. It is claimed that the slabs having been thoroughly formed and therefore expanded to the fullest dimensions prior to the making up ot the plate, it is impossible for them to exert any pressure on the metal frame, and that there is therefore no tendency to buckling (see p. 560). Plates of this type are lighter than the ordinary

FIG. 265.



pasted plate for a similar output, the relative amount of active material being considerably greater.

The method of making up lithanode negative plates is somewhat similar to that adopted for the positive plate, the slabs being, however, reduced to the state of spongy lead.

These cells were originally designed by Messrs. Fitzgerald and Frankland, many of the practical details having been worked out by Mr. Niblett. The manufacturers have paid considerable attention to the production of small cells, as well as to those for ordinary

lighting purposes; and one of the most useful type, which is small, light, and of very simple construction, consists of two plates, one of peroxide and the other of spongy lead, mounted in an ordinary test tube, the plates being held in position and the solution prevented from escaping by means of a quantity of insulating material which is run into the upper part of the tube, a small vent hole being left for the escape of any gas which may be generated. In a still smaller and more compact cell the case is of vulcanite, the total weight being 2½ ounces. When discharged at a rate not exceeding one-fifth of an ampere the discharge can be maintained for about twenty minutes, smaller currents being maintained for a proportionally longer time. A special form of vent plug is provided to prevent the leakage of the solution in the event of the cell being overturned.

Secondary cells are usually delivered by the makers in a dry state and uncharged, and in making them up prior to charging, the solution should be poured in to the height of about ½ an inch above the negative plates. It should contain about 20 per cent. of pure sulphuric acid, and have a specific gravity of 1·170 (that is, if a given volume of water weighs say 1 pound, the weight of an equal volume of the solution should be 1·170 pound); but it will be seen from the equations already given that in the process of charging some of the water in the cell is changed to sulphuric acid, and this causes the proportion of the latter to rise to about 25 per cent., increasing the specific gravity to about 1·220. This accretion of sulphuric acid, which is, however, lost on discharging the cell, is accompanied by an increase in the conductivity of the liquid to the extent of about 10 per cent.

An instrument for measuring the specific gravity of the acid solution becomes, therefore, a necessity. Such a piece of apparatus is called a hydrometer, or, for this special case, an acidometer, a useful form being that shown in fig. 266, which is simply a glass tube weighted at the bottom with a quantity of small shot. The lower the specific gravity of the solution, that is to say, the lighter it becomes bulk for bulk, the deeper will the hydrometer be immersed. As the liquid increases in density the instrument becomes relatively lighter and therefore rises. Consequently, the scale on the tube can be made to indicate the relative density corre-

sponding with the various depths to which the tube descends. Another useful form is that known as Hicks' hydrometer (fig. 267), which consists of a flattened glass tube with the upper end bent over so as to allow it to hang on the edge of the glass containing-vessel, the tube being also perforated to facilitate the free circulation of the solution. Inside the tube are four small glass globules containing liquids of different specific gravities and different colours; each globule rises and falls at distinct specific gravities, and allows thereby the relative density of the solution to be very readily observed.

FIG. 266.

FIG. 267.

During the discharge the density of the solution falls until, when the cell is practically exhausted, it is only 1·150. The relative density of the solution thus affords an excellent means of ascertaining the condition of the cell. It may also be observed that the colour of the plates affords another good indication of their condition, the peroxidised positive plate being, when in proper condition, of a brownish or deep reddish hue, the negative or spongy lead plate being coloured grey or slate tint. There is thus a marked distinction in the colouration, which should always be discernible.

There are various explanations of the chemical changes which take place in a secondary cell, but although many of the most brilliant chemists of the day have devoted considerable attention to the subject it is still shrouded in doubt, and there seems but little probability of a general concurrence of opinion as to what actually takes place. The difficulty arises from a number of intermediate or secondary reactions which, it is assumed, take place during the processes of charging and discharging.

We are, however, more particularly concerned with the final rather than with the intermediate stages, and will therefore assume that our plates, whether they be of the Planté or of the pasted type, have been duly formed and charged, so that the positive plates have been coated with lead peroxide (PbO_2) and the negative plates reduced to the state of spongy lead. The condition of the cell can then be represented by the symbols :—

$$\underset{\substack{\text{Lead}\\\text{peroxide}}}{PbO_2} + \underset{\substack{\text{Sulphuric}\\\text{acid}}}{SO_4H_2} \ \ldots \ \underset{\substack{\text{Sulphuric}\\\text{acid}}}{SO_4H_2} + \underset{\text{Lead}}{Pb}.$$

This means that the active material on both plates is in contact with the sulphuric acid solution. If now the cell is discharged the two plates are partially converted into sulphate of lead, and the changes which take place can be represented by the following equation :—

$$\underset{\substack{\text{Lead}\\\text{peroxide}}}{PbO_2} + \underset{\substack{\text{Sulphuric}\\\text{acid}}}{SO_4H_2} \ldots \underset{\substack{\text{Sulphuric}\\\text{acid}}}{SO_4H_2} + \underset{\text{Lead}}{Pb} = \underset{\substack{\text{Lead}\\\text{sulphate}}}{PbSO_4} + \underset{\text{Water}}{OH_2} \ldots \underset{\text{Water}}{OH_2} + \underset{\substack{\text{Lead}\\\text{sulphate}}}{PbSO_4}$$

Combining the changes on the two plates into a simple chemical equation, we get

$$PbO_2 + 2SO_4H_2 + Pb = 2PbSO_4 + 2OH_2.$$

We thus see that for every atom of lead attacked during the discharge both on the positive and on the negative plates, a molecule of sulphuric acid is decomposed, and the solution is further diluted by the formation of a fresh molecule of water. When the plates have been more or less completely converted into lead sulphate, no further current can be obtained. This should be evident when it is remembered that the first essential in a battery cell is to obtain two plates whose surfaces are dissimilar. The cell having been discharged, a further charging operation is therefore necessary before any further current can be obtained. The chemical effect of the charging current is exactly the reverse of that which results from the discharge, as will be gathered from the equation :—

$$PbSO_4 + OH_2 \ldots OH_2 + PbSO_4 = PbO_2 + SO_4H_2 \ldots SO_4H_2 + Pb\,;$$

or, again, combining the two changes, we get

$$2PbSO_4 + 2OH_2 = PbO_2 + 2SO_4H_2 + Pb.$$

The reversal is thus very complete ; the two plates are reduced from lead sulphate to lead peroxide and spongy lead respectively, while the solution regains the sulphuric acid which was extracted from it during the discharge. The water which was formed during the discharge is also completely absorbed during the charge.

These reactions, however, affect only a portion of the plates ; in fact, the active portion of the cell is usually less than that which remains passive.

Fig. 268, which is very instructive, is the outcome of a series of experiments by Messrs. Ayrton, Lamb, and Smith, as well as of a number of chemical analyses by Mr. Robertson. A cell which had been carefully worked, and was therefore in good condition, was charged in the ordinary way for 14½ hours with a current of 9 amperes. The gradual rise in electro-motive force is indicated by the dotted curve. The cell was then discharged for about 12 hours at the rate of 10 amperes. During the next charge, however, which is indicated by the continuous curve, the positive plates were temporarily removed from the cell at the points marked A, B, C, and D, when the terminal potential difference of the cell was 2·134, 2·2, 2·234, and 2·4 volts respectively, and some of the pellets were forcibly removed and subjected to chemical analysis. The interval that elapsed during the removal of the pellets (about twenty minutes on each occasion) is not shown in the curve, the potential difference indicated a few seconds after again closing the circuit being the same as that which was observed at the moment of disconnecting the charging current. The pellets were taken from the top, middle, and bottom of the plates, and every care was exercised to avoid the introduction of any disturbing element, or anything likely to prejudice the results of the analysis, which showed (fig. 268) that the percentage of lead peroxide contained in the pellets increased as the charge progressed. Similar experiments were made by removing pellets during the discharge, and it was found that the percentage of PbO_2 fell at approximately the same rate as that at which it rose during the charge. An interesting feature brought out in these analyses is that 48 per cent. of the PbO_2 found in the peroxide pellets does not suffer conversion into lead sulphate, that is to say, it exceeds by this

amount the quantity actually essential to the reactions. The explanation is that the sulphate of lead which is developed forms an

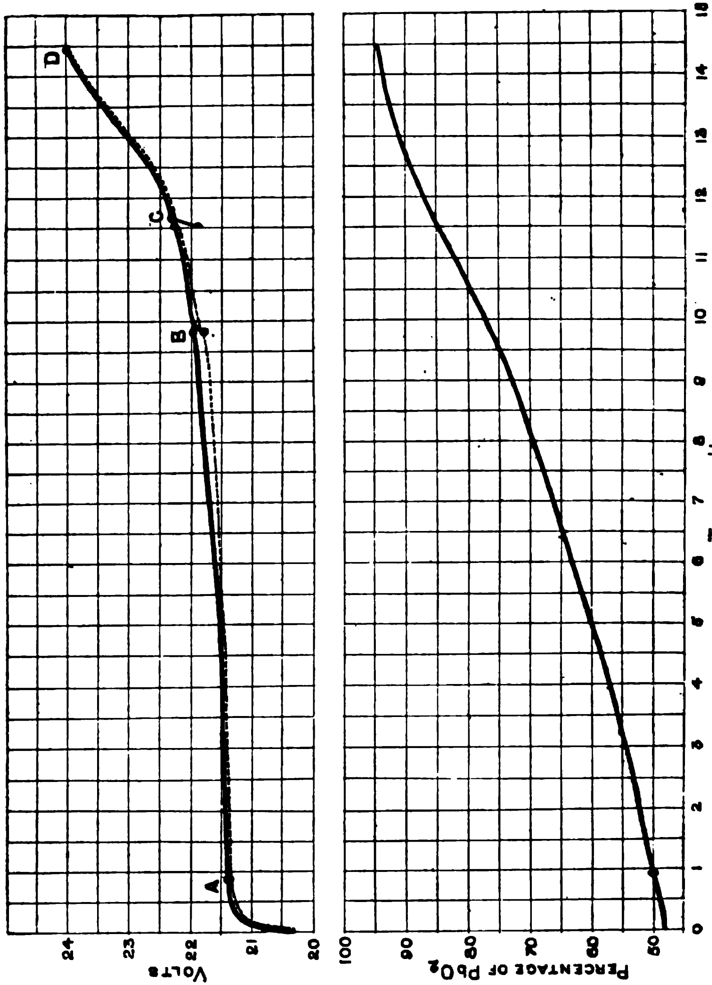


FIG. 268.

impervious coating over the surface of the pellets, and thus prevents the action from extending to the inner particles.

Mr. Robertson's analyses may be thus summarised—

'(*a*) The particles of the peroxide very soon get coated in the discharge with a layer of lead sulphate, which protects the peroxide from further action.

'(*b*) The analysis also shows that a large proportion of active material is still remaining at the end of the discharge.

'(*c*) The loose powdery surface of the positive plate seems to be thoroughly converted into lead sulphate.

'(*d*) When the peroxide on the surface of the plate falls to about 31 per cent. the cell loses its E.M.F. very rapidly, owing to the inactive layer of sulphate impeding the action of the sulphuric acid on the active material behind it, and also to the formation of peroxide on the negatives. The "diffusivity" of the acid is also then decreasing, while it has to penetrate further into the plate to find active material. When the whole of the paste approaches this composition of 31 per cent. peroxide, the cell loses its E.M.F. entirely.

'(*e*) The action seems to take place most rapidly where the current-density is greatest; the plate gets hard there from sulphate soonest on discharge, and oxidises quickest on charge.'

It has been observed by Planté as well as by Messrs. Gladstone and Tribe, that during the discharge of a cell a certain amount of peroxide is formed upon the negative plate, so that when the peroxide is thus formed at a greater rate than it is reduced by the acid, the two plates, positive and negative, must rapidly approach a state of electrical equilibrium. Further, when the circuit is broken, local action alone can take place, the effect of which is to reduce the peroxide on the negative plate; that is to say, the peroxide will be deprived of its oxygen. Consequently, on re-making the circuit, the cell will again give a current. This idea has been used by Messrs. Gladstone and Tribe to account for the so-called recuperative power of a cell, as well as for the rise of electro-motive force which is observed on breaking the discharging circuit. It is a matter of general knowledge that if a cell be discharged so far that it will yield only a very feeble current—so far, that is to say, that its electro-motive force has fallen almost to zero—it will, after a period of rest, be found to have a considerably higher electro-motive force than at the moment when it was

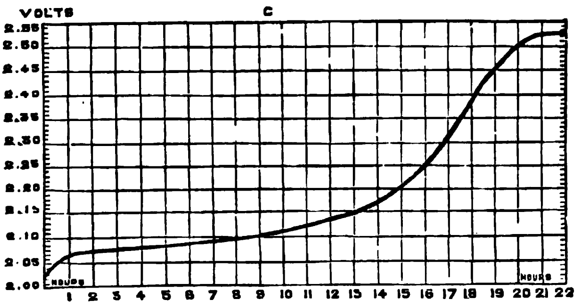
disconnected; and that this recuperation enables it to send a comparatively strong current through the circuit.

It will be evident that while it is essential that great care should be exercised in the manufacture of secondary cells, the treatment to which they are subjected is a matter of at least equal importance.

The charging current should be proportional to the number of plates, and, for the Electrical Power Storage Co.'s L type of cell, should be equal to about 4 amperes per positive plate, so that the 15-plate cell requires from 25 to 30 amperes. When the current exceeds this amount, it cannot increase the reduction of the sulphate of lead in proportion to the extra amount of current, and the surplus current is therefore wasted in the decomposition of water and the premature evolution of bubbles of oxygen gas from the positive surface, a phenomenon which is technically known as boiling. There is also a risk that the too powerful current will cause bending or buckling of the plates, which, being close together, stand a good chance of making contact one with the other, and so short-circuiting the cell. Precaution has also to be taken that the electro-motive force of the charging current shall exceed that of the subsequent discharging current by about 10 per cent., or be at the rate of about 2·5 volts per cell, being, however, a little lower at starting than when approaching the completion of the charge. This should be evident when it is remembered that the counter electro-motive force of the cell rises as the charging and consequent chemical reactions progress; for example, if the cell is so far charged that its electro-motive force is 2 volts, it would require a smaller applied potential difference to urge a current of 30 amperes through it, than would be necessary when the electro-motive force of the cell has been raised to 2·5 volts. In practice the object is usually attained by switching cells out of the circuit, one or two at a time, as the electro-motive force of the battery rises. The potential difference of the charging dynamo can then be kept constant. The charging should be continued until the solution 'boils' or assumes a milky appearance, consequent on the evolution of free oxygen, the positive plates having been then oxidised as far as possible, or having absorbed as much oxygen as they can take up.

The E.M.F. of a secondary cell, as was shown in fig. 268, does not rise uniformly with the continuance of the charging current. In some experiments, performed by Messrs. Drake and Gorham with a battery of 15 cells, a current of 22 amperes was employed, by which the E.M.F. was raised from 2·02 to 2·53 volts per cell. The variations in the rate of increase are shown in fig. 269, from which it will be seen that after 220 ampere-hours had been put in, that is to say, after a charging current of 22 amperes had been maintained for a period of 10 hours, the E.M.F. had risen gradually to 2·13 volts. After about 14 hours charging, when the E.M.F. was 2·17 volts, a somewhat sudden rise in E.M.F. was observed, which was continued until 2·53 volts were registered. The maximum

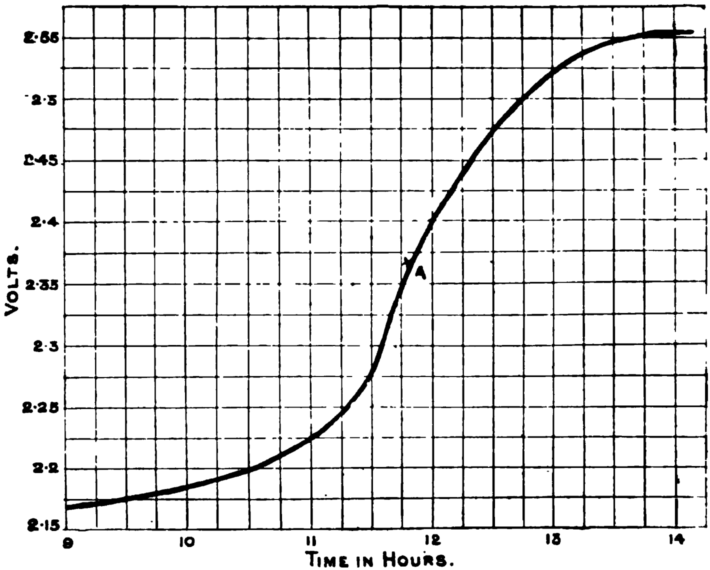
FIG. 269.



E.M.F. usually obtained is 2·5 volts, at which point gases are freely evolved, and cause the milky appearance already referred to. It was for some years considered to be very injurious to charge the battery to an E.M.F. exceeding about 2·25 volts per cell, it being thought that charging beyond this point, or overcharging as it was called, was responsible for the remarkable tendency of the plates to buckle or twist out of shape, and so to loosen and detach the pellets. This, it was supposed, was brought about by the freed oxygen destroying the grid. It has, however, been conclusively proved that overcharging is not only harmless, but actually beneficial. In the experiments previously referred to, some cells were charged without cessation in order to ascertain the exact amount of current necessary to destroy the grid. It was

soon evident that the process was, at any rate, a slow one ; but the experiment was continued, until the full prescribed current had been passed through, for more than two months. At the end of that time it was found that the lead conductor was practically as sound as before charging. The coating of fine peroxide formed on the surface was very thin ; there was no sign whatever of buckling, and, further, the specific gravity of the solution, when the cells were left in their then fully charged condition, remained

FIG. 270.



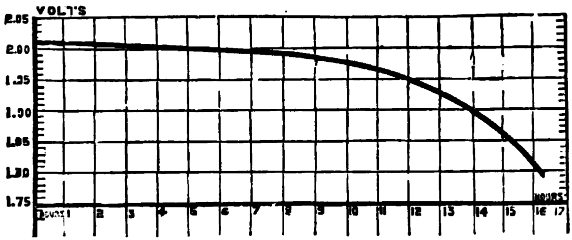
absolutely unaltered. The conclusion thence drawn was that the oxidisation of the grid caused by charging only penetrated to a very limited depth, and that the coating of fine peroxide thus formed, actually protected the grid from excessive local action ; and it was established that the life of the grids was not limited by the amount of charging, *i.e.* by the number of ampere-hours put into a cell. We shall return to this question presently.

Professor Ayrton and several of his assistants have more

recently obtained a valuable series of curves, one of which is reproduced in fig. 270. In this case the cells were charged with a current of 9 amperes. The rise in potential difference was slow and steady up to about 2·15 volts per cell, but then became much faster, until a maximum of 2·55 volts was obtained. The most rapid increase occurred at about the end of the twelfth hour of the charge, as indicated at A in the figure. The similarity between this curve and that given in fig. 269 is very noticeable.

During the discharge the E.M.F. of the cells speedily falls to about two volts each, the higher initial electro-motive force being mainly due to the presence of hydrogen on the spongy lead plate. When this has been oxidised there remains the lead surface between which and the peroxide plate the electro-motive force falls very slowly to about 1·98 volt. The fall is then slightly faster,

FIG. 271.

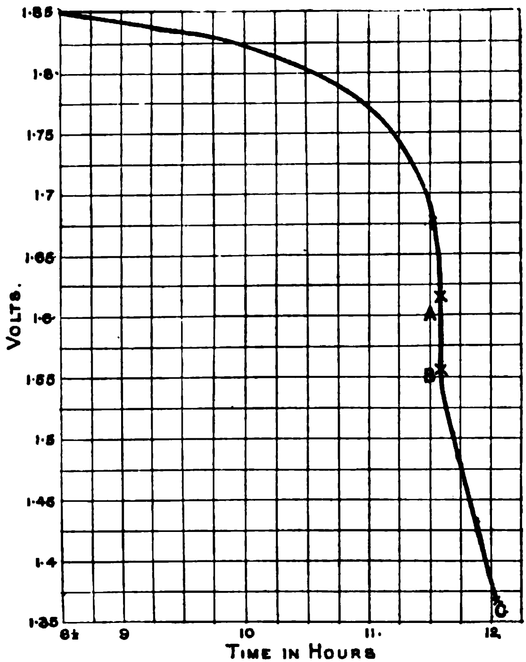


although, as was found by Messrs. Drake and Gorham in the series of experiments previously referred to, after an output of 400 ampere-hours at the rate of 25 amperes, the total drop from the time that the cell settles down to steady work at 2·02 volts, is only about 10 per cent. The rate at which the fall of E.M.F. took place is clearly shown in the instructive curve given in fig. 271. The discharge was continued until the E.M.F. was only 1·80 volt per cell, which is a point about 0·1 lower than in practice it is advisable to go. With a fall to 1·90 volt the difference is only about 5 per cent.

In an experiment performed to ascertain the effect of a rapid discharge upon the plates, a battery was divided into two halves, one of which (A) was repeatedly run out, but the other (B) was never discharged beyond the point at which the E.M.F. commenced

to drop. The experiment extended over a considerable time, but gave the instructive result that when exactly the same number of ampere-hours had been taken out of each half, the plates of (A) showed signs of expansion or growing and consequent buckling, whereas in those of (B) no change could be detected. The life of the grid was therefore proved to be dependent not on the

FIG. 272.

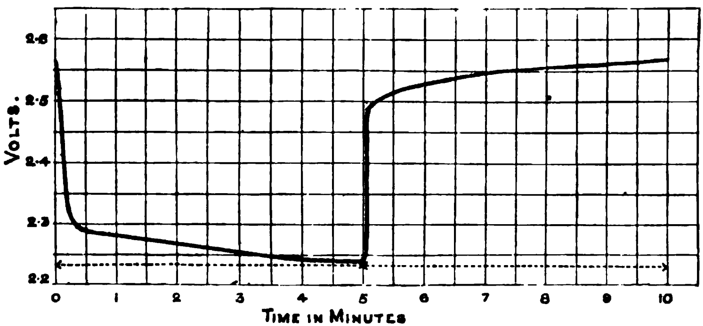


amount of ampere-hours taken out, or on the work done, but on the treatment of the plates; that is to say, upon the rate and extent to which the cell is discharged.

Fig. 272 is a portion of the discharge curve obtained by Professor Ayrton and his collaborateurs, but it differs from that given in fig. 271, in that the discharge, which was at the rate of 10 amperes, was continued until the potential difference was reduced to 1·35

volt, and the rapidity with which this potential difference falls from about 1·75 volt is very remarkable. Another very instructive curve obtained from the same series of experiments is that given in fig. 273. The cell was charged with a constant current of 9 amperes until a potential difference of 2·56 volts was obtained. The charging circuit was then broken, and immediately there was a fall to 2·31 volts, followed by a steady fall during the next five minutes to 2·24 volts. On again closing the charging circuit there was an instantaneous rise to 2·48 volts, followed by a steady rise during the next five minutes to 2·56 volts. In subsequent experiments it was ascertained that the fall of potential difference on disconnecting the charging circuit, became more rapid as the charge increased.

FIG. 273.



Several explanations have been advanced to account for the fall in the electro-motive force as the discharge progresses, but perhaps the most correct one is that of Messrs. Gladstone and Hibbert, who have probably done more than any other workers to ascertain and explain the phenomena connected with secondary batteries, and who maintain that the variation in the electro-motive force is consequent upon the variation of the density of the acid solutions in the immediate neighbourhood of the plates. The somewhat sudden changes in the potential difference of a cell, observed during charging, may possibly be due in the first case to the break in the continuity of the film of lead sulphate, and secondly to its complete disappearance. The reverse of these phenomena may

also be held to account for the sudden changes in the potential difference during the discharge. These points were not urged by Messrs. Gladstone and Hibbert. Neither did they essay to explain the fact that it is safer to allow a cell to rest for a prolonged period after a charge, than after a discharge. There seems, however, no reason why, if their theory be correct, we should not employ that theory to explain the fact. It has already been shown that the density of the acid solution is greater when the cell is in the charged state, than when it is in the discharged state; and we can easily infer that, when the cell is allowed to rest after a charge, the comparatively dense solution will cause, by local action, the development of a certain amount of pure lead sulphate, whereas when in the discharged state the solution is so weak that it is partly employed in simply oxidising the lead, this oxide uniting with the lead sulphate formed during the discharge so as to produce a troublesome white sulphate of lead, to which we may now refer.

It should be observed that by the time the E.M.F. of a cell discharged in the ordinary way has dropped to 1·90 volt the greater portion of the surfaces will have resumed the condition of lead sulphate ($PbSO_4$), and there will then be considerable risk of the formation of a more obdurate form of sulphate, which may be expressed by the symbol Pb_2SO_5, and which is caused probably by the $PbSO_4$ combining with the monoxide or PbO. This is a hard white sulphate and is very troublesome. It is insoluble, non-conducting, very adhesive, and covers both the pellets and the grid, and in very bad cases forms on the inside of the plate between the grid and its pellets. When it falls off the plate, it generally carries with it some of the active material, which is therefore wasted. It is consequently advisable that the E.M.F. of the individual cells should be tested periodically with a special low-reading voltmeter. Two or three of these instruments were described in Chapter VI. The experiments of Messrs. Drake and Gorham showed that buckling was almost invariably accompanied by the formation of the hard sulphate on the face of the plates, and that this enamelling could be prevented by charging, and was not due to impurities in the oxides or acid used; further, that when the plates were free from sulphate there was no tendency to buckle. In the case of the first use of cells, when the acid

was put in, the specific gravity dropped in spite of the charging, indicating the formation of sulphate; by persevering in charging the sulphate disappeared, and with it the tendency to buckle. It is therefore evident that in order to avoid buckling of the peroxide plates, cells on their first use (whether new or after long disuse) should be charged incessantly until they have been considerably overcharged.

It has been ascertained that in almost every case where abnormal disintegration takes place, the plugs of active material fall out of the plates in complete halves and in very hard condition; and analysis has shown that they contain an excess of sulphate, due to insufficient charging. On the other hand, in a few instances the active material has been found to have become disintegrated and fallen off in a fine powder, and this was specially observable when on account of a leak in the containing-vessel and consequent frequent addition of water, the solution had become abnormally weak. In this case practically no sulphate was present, and the mass simply lost cohesiveness.

It would seem, then, that a certain proportion of sulphate in the material is necessary to bind it together, but that excess must be avoided.

As has already been intimated, buckling is due to the expansion of the paste during sulphating, for lead, being a very ductile but non-elastic body, the grid does not re-assume its original shape when the subsequent partial contraction of the paste takes place, and to this must also be attributed the loosening of the pellets. The contraction being but partial, the positive plates become gradually increased in size with continued use. Owing to the stretching effect of the paste, it is necessary that the grid should be of equal strength throughout, and not made stronger in one direction than in another. Efforts have been made to harden the grid by the admixture of a small percentage of antimony, but the results have not proved satisfactory, owing, among other things, to the difficulty experienced in making the alloy of uniform proportions throughout.

Mr. Reckenzaun found that a positive plate which had when new a surface of 90 square inches, grew to 94·76 inches after one year's daily use, while others showed when almost worn

out an increase of 7 square inches; these measurements being simply the product of the length into the breadth of the plate, and independent of corroded or oxidised furrows. The actual amount of surface in contact with the liquid is considerably greater than these figures would indicate, owing to the irregularities produced by the solution.

When the rate of discharge is excessive, there is considerable risk of causing unequal expansion of the plates, resulting sooner or later in buckling, loosening of the active material, and short-circuiting. It is impossible to prevent a certain amount of the obdurate sulphate forming, and this, being an insulator, reduces the available active surface and increases the resistance of the cell. As already indicated, considerable difficulty is experienced in removing this sulphate, and under any circumstances a certain amount of disintegration of the peroxide is sure to ensue.

But experiments have been performed which tend to show that with a considerable increase in the charging E.M.F. the sulphate can be decomposed. This is, however, a very tedious, expensive, and uncertain operation; but the formation of the sulphate can be to some extent prevented, by the introduction of a small percentage of sodium sulphate (Na_2SO_4). Mr. Barber Starkey has also found that cells which have been very badly sulphated can be renovated by the addition of a small quantity of carbonate of soda (common washing soda). He says that a very badly treated battery after it had been supplied with some of the carbonate of soda, improved rapidly, every trace of the formerly intractable white sulphate disappearing, and the plates presenting a perfect appearance. Subsequently the battery worked well for several years. This salt must, however, be added carefully, as there is some risk of its causing a disintegration of the pellets. One ounce of soda to a gallon of acid solution is given as a good proportion.

If the cells are discharged and then left to stand idle for any length of time, the sulphating takes place rapidly, and causes premature buckling; the formation of the white sulphate probably arising in this case, as was indicated on p. 566, from the comparative weakness of the solution.

The life of a positive plate is not, however, so brief as might be anticipated from the many little difficulties which beset it,

for with fair and continuous usage its life amounts to about three years. The decay of the plate is more rapid in the lower than in the upper half, owing probably to the greater density of the acid solution in that portion of the cell. The life of a negative plate, which is subject to but few of the troubles attending the positive plate, has been estimated at ten years, although it remains for time to demonstrate the truth or otherwise of this assumption. The Electrical Power Storage Co. claim that the positives of the K type even when roughly used, as in traction work, will sustain from 800 to 1,000 discharges.

The capacity of a cell may be defined as the amount of energy it is capable of storing, and is calculated generally in ampere-hours, that is to say, it is the product of the number of amperes at which the cell is able to discharge, into the number of hours through which it can maintain that discharge. Capacity is also estimated by the ratio between the weight of the material and the electrical output. The amount of surface exposed to the solution really determines the charge which a cell can receive, and is therefore a measure of its capacity.

The capacity of a cell is an important consideration, seeing that the prime cost is considerable, that the cell is bulky and therefore requires correspondingly ample accommodation, and that only a portion of the plate is utilised. The capacity can be increased by more thoroughly 'forming' the paste and reducing the proportion of solid metal, which we may call so much dead weight, but it is not safe to carry this reduction much farther than has already been done, or there will be considerable risk of the plate being unable to bear its own weight, and therefore of its falling to pieces.

Many attempts have been made to use other electrodes than lead for secondary cells, but so far with little success. Thus one was brought out in which there was a lead plate to be peroxidised, the other plate consisting of copper to be alternately dissolved and deposited from a copper sulphate solution ; but the low electromotive force of this cell precluded its adoption. For somewhat similar reasons the employment of other suggested solutions has been found to be impracticable, and there is therefore no need to further discuss them here.

Coming now to the question of 'efficiency,' or the ratio of the energy taken out of the cells as compared with that put into them, the former can, of course, never equal the latter. The phenomenon of boiling, for example, is an evidence of energy being wasted, for the current is then employed in the unproductive decomposition of water. It is often asserted that secondary cells are capable of giving out 80 or more per cent. of the energy put into them, and this may be true with small cells wholly but slowly discharged; but the experience of those who have given the matter long and earnest attention is that the efficiency of cells of the ordinary sizes, discharged, at the normal rate, to their proper minimum E.M.F., ranges between 65 and 75 per cent. Even then great care has to be taken that the charging current is of the right strength and potential difference, and that the cells are maintained in the best possible condition. The efficiency of a cell depends, as will probably have been gathered from what has already been said, very largely on the rate at which the energy is discharged, that is to say, it depends upon the current strength per unit of surface, or, as it is technically termed, upon the 'current density.'

The highest safe rate, which has been already stated to be—for cells of the L type—4 amperes per positive plate, is equal to 0·01 ampere per square millimetre of surface, and it may be stated generally that the lower the density, the greater the efficiency. With a 25-ampere cell discharging at the rate of 5 amperes, an efficiency of 90 per cent. might be obtained, but on increasing the current to 40 amperes, the output falls to about 50 per cent., for when the rate of discharge is high, the E.M.F. is rapidly reduced. It is for this reason that with the 15-plate cell previously described, the discharge should not exceed 30 amperes, and if fully charged, such a cell can maintain this current for 10 hours, indicating a commercial capacity of 300 ampere-hours. Similar results were mentioned when speaking of the various forms of cells described in this chapter, and it may be generally accepted that the lower the rate of discharge, the higher is the efficiency. When the charging current is excessive there is also considerable loss or waste of energy, which arises from the unproductive boiling. The average internal resistance of a cell containing 31 L-plates is but 0·001", and it is therefore very easy to incur even a greater

loss in the connections of a battery, than in the battery itself. Such losses of course reduce the efficiency of the battery.

It remains now to consider the general utility and application of secondary cells, which may be classed under three heads, viz. storage, regulation, and distribution.

As a means of storing energy to be afterwards converted into a current of electricity, the secondary battery stands alone. It is often compared to a domestic water cistern, but the analogy is not a very happy one, for the cistern receives a periodical heavy charge of water to be delivered in small or large quantities as required, while the battery usually receives its charge gradually or even intermittently as opportunity arises, whereas its rate of discharge often approaches the highest possible, and frequently exceeds the charging rate, when, of course, the duration of the discharge is considerably shorter than that of the charge.

One of the greatest obstacles to the more general adoption of the electric light is the practical impossibility of storing energy by any other means than that afforded by expensive secondary batteries. Moreover, as the areas to be supplied from a generating station are getting larger, and promise to increase in extent, the potential difference applied to the distributing conductors is being proportionally increased, amounting generally to 1,000 or 2,000 volts; and as the secondary cell has a working electro-motive force of but two volts, it is generally impracticable to employ such apparatus at the generating station to meet even the small demand during the daytime, and at such other times as are characterised by a very small output.

It is because of these and other difficulties that where these high voltages are used, alternators are employed, thereby giving the advantages already referred to, and making the ordinary electro-magnetic transformer available. In fact, apart from its storage properties, the secondary battery is to direct current working what the transformer is to alternate current working, and such a battery is sometimes described as a battery-transformer. It would nevertheless be an inestimable boon if some device could be employed, to be to electricity generating stations what the gas-receiver, or the so-called gasometer, is to the gas-works. Although, however, the secondary battery is hardly likely to be

employed to any great extent in public lighting works, it offers very many advantages for comparatively small or private installations. In such cases direct current working is the rule; but it is rarely desired to keep the generating plant—that is to say, the engine and dynamo—running day and night, but rather to run it only during the hours when the load is heavy, and to trust to the secondary battery to supply the required current at other times. There are also cases in which it is desired to charge the battery at the same time that other classes of work are being done by the engine, possibly during the light hours of the day, and to draw upon the battery for lighting purposes after the engine has been stopped.

Secondary cells have also the advantage that, where they are used in sufficient numbers to maintain the ordinary number of lamps, they can, on emergency, be employed to considerably increase the total amount of current supplied. For example, suppose the dynamo to be able to generate the same amount of current as the secondaries can discharge, the latter can be charged during the day, and both dynamo and battery employed either independently or together for lighting purposes in the evening.

There is another advantage pertaining to the use of secondary cells consequent on the fact that it frequently happens that the employment of an engine and dynamo in or near the house for electric-lighting purposes is inconvenient, on account of noise, smell, &c. In such cases the current can be brought to the battery in the house, by wire from the dynamo, and the energy there stored up for future use, machinery of every kind being thus kept out of the house.

Many other instances where the storage capacity of secondary cells is of inestimable value will probably suggest themselves to the student, but in nearly every case arrangements must be made which will permit of the dynamo supplying current to the external circuit at the same time that it is charging the battery. There is, however, one class of work in which the secondary battery fulfils a function in a manner peculiar to itself, and that is in the propulsion of launches and other comparatively small vessels. Nothing can be more objectionable in such cases than the dirt, noise, and smell attendant upon the employment of steam power,

while it is almost impossible to conceive anything more clean, silent, and agreeable than a secondary battery placed in lead-lined teak boxes, stowed in the hold or under the seats, and charged as required from a generating plant erected on the banks of a river, or other equally convenient spot. A word of caution is, however, necessary, and that is that ample ventilation should always be afforded for the escape of the hydrogen and oxygen gases which are evolved during the charging, otherwise there will be some risk of an explosion.

Secondary batteries are also employed for the propulsion of tram-car, and even of ordinary road vehicles. In these cases it is usual to have the batteries arranged in trays, and then to slide them in and out of the cars or carriages between the journeys. This method of propulsion has so far met with but limited success, chiefly on account of the comparatively low efficiency of secondary batteries and the great cost of wear and tear. These are the points to which attention is at present being directed, and if any material improvement can be effected in these directions, there will probably be an enormous increase in the application of batteries to this class of work. It must be remembered that a car with a secondary battery and motor is perfectly self-contained, and has no need for either a more or less unsightly overhead conductor, or the much more expensive underground conductor built into a conduit running between, and parallel with, the rails. These systems, it will be remembered, were dealt with in Chapter XII.

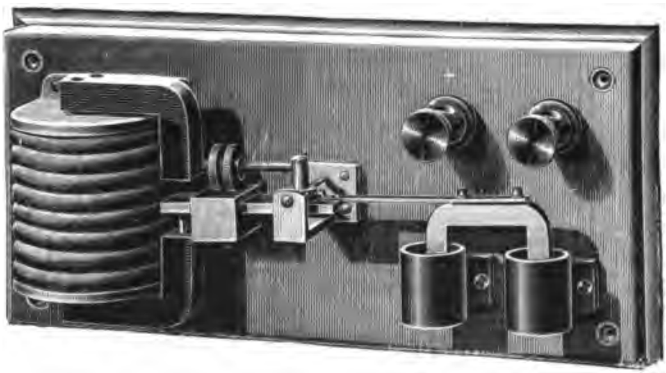
A secondary battery is pre-eminently serviceable as a regulator for maintaining a uniform potential difference, more particularly in cases where the dynamo is driven by a gas or oil engine, and where, in consequence of the irregular and comparatively infrequent impulses imparted to the driving wheel, the potential difference developed by the machine is subject to considerable variations. Let it be supposed, for example, that a shunt-wound dynamo is employed, with the aid of a secondary battery, to supply current to a number of lamps joined up in parallel. Let the lamps be made to take a pressure of 100 volts, and let it be supposed for the moment that the battery has been charged to a pressure of 102 volts, and that the dynamo at each impulse of the engine develops for a moment 110 volts. Between these impulses

the dynamo pressure may fall, and when an explosion is 'missed,' it may even fall, in the absence of the battery, below 100 volts. The battery, however, tends to correct these irregularities. Should the electro-motive force of the dynamo fall below that of the battery, the latter will augment the current through the field-magnet of the former, and in the right direction for working. The strength of the field will therefore be increased, and, the current in the armature being at the same time diminished, the speed of the engine will be accelerated and a higher E.M.F. developed. The battery will at the same time maintain the proper voltage on the lamp terminals. On the other hand, the pressure of 110 volts obtained at the moment of the impulse will be too high for the lamps, but in that case the cells form a low resistance shunt to the lamp circuit, and they take up or absorb the superfluous volts, a strong current being urged through them and increasing their charge.

In some cases, more particularly where constant attendance is not provided, an automatic switch is employed which, in the event of the dynamo pressure falling materially, cuts out the machine and causes the circuit to be fed from the battery alone. It is quite conceivable that the driving belt might break, or the supply of gas for the engine be accidentally cut off, and in such cases the dynamo pressure would of course fall at once, with the result that, unless the dynamo promptly responded and continued to run as a motor, the battery would send such a strong current through the low resistance armature as would suffice to burn it up. There are several automatic switches designed for preventing a disaster of this sort, one of them, the 'Nevile' automatic switch, being illustrated in fig. 274. It consists of an electro-magnet, with projecting pole-pieces bent over so as to nearly meet. Between them there is a balanced permanent steel magnet, which can rock horizontally. To the further end of the magnet is attached a non-magnetic rod, which carries a copper fork. The electro-magnet is in the main charging circuit, and the pole-pieces are magnetised one way or the other, according to the direction of the current. If the dynamo pressure falls, the current passes from the battery to the machine, and makes the polarity of the lower pole-piece opposite to that of the adjacent

end of the magnet, which is consequently drawn down, the copper fork being thereby raised, and breaking contact with the mercury contained in the cups beneath it. The charging circuit is thereby disconnected. When the dynamo pressure exceeds that of the battery, the direction of the current through the electro-magnet—and, therefore, the polarisation of the pole pieces—are reversed. Consequently, the magnet is drawn up, the fork dipping again into the mercury, and re-making the charging circuit. Mercury switches are objectionable where the potential difference at the moment of disconnection is considerable, but in this case the switch can be adjusted so as to act when the difference between the pressure of

FIG. 274.



the dynamo and that of the battery is very low, and in that case the spark caused by the breaking of the circuit would be very small.

Another useful piece of apparatus is an automatic alarum, the object of which is to indicate when an excessively high current is being drawn from the cells. In one of these alarums a vertically fixed solenoid, consisting of a few turns of thick wire, is placed in the main circuit. When the current exceeds a certain prescribed limit, the soft iron core is attracted, and a horizontal spring attached to it completes a local circuit, causing one of the cells to send a current through an ordinary electric trembler bell.

In addition to these, there are many other pieces of apparatus,

ingenious in their way and useful for special purposes, which however we need scarcely describe.

The use of a regulator switch, such as that illustrated in fig. 275, shouid, however, be understood. It will be remembered that the working pressure of a secondary battery ranges from 1·9 to 2·4 volts per cell. If, therefore, a pressure of 100 volts has to be maintained, a battery of 53 cells will, when their pressure has fallen to 1·9 each,

FIG. 275.

be required. But 53 cells when fully charged would have an electro-motive force of nearly 135 volts. Hence the dynamo must be capable of developing this potential difference. If, however, the whole of the fully charged cells were to be joined direct to the lamps, the result would be that they would all break. It follows, therefore, that a regulating switch is necessary, by the use of which the number of cells being charged and the number feeding the lamps may be independently varied. In the switch illustrated the

positive terminal of the charging dynamo is usually connected to the left-hand lever, while the corresponding main leading to the lamps is connected to the right-hand lever. These levers can be moved independently over the switch-bars fixed on to the slate base. The cells near the positive end of the battery are connected, one to each of these bars. If, therefore, both the levers are in contact with the top bar as illustrated, the full battery is connected both to the dynamo and to the lamps. This rarely happens, the more general method being to have more cells under charge than are connected to the lamp circuit, so that the right-hand lever is usually a few bars below the other. The number of cells cut out of the lamp circuit varies, of course, with their electro-motive force. When, for example, the cells are charged up to a pressure of 2·4 volts per cell, then 42 cells will suffice to maintain the lamp-pressure, the other 14 being cut out. The cells in use vary, therefore, from 42 to 53, according to their condition. Instead of having a switch with fourteen bars, it is the practice to connect two or three cells in series to one or two of the bars, but this practice must not be adopted too extensively, as the movement of the lever from bar to bar will vary the volts too rapidly for good working. It will be noticed that the number of cells required to feed the lamps must always be increased when the dynamo is disconnected. This arises from two causes, first that the electro-motive force of a secondary cell falls when the charging current is switched off, and secondly that the potential difference obtained from a portion of a battery, which is, at the same time, receiving a charge, is made up of two parts, viz. the electro-motive force of the battery itself plus the electro-motive force which has to be applied in order to urge a charging current through the battery.

CHAPTER XV.

ARC LAMPS

IN this and the following chapter we have to deal with the question of illumination, and it must be borne in mind that illumination is the whole object of lighting, so that it is very essential that the student should be careful to discriminate between the amount of light developed by any particular source and the resulting illumination—that is to say, the relative effectiveness with which that light is distributed and utilised. It would be a grand achievement if we could by artificial means approach ordinary sunlight in quality, in quantity, or even in uniformity of distribution. This, however, we cannot hope to do. The light emitted by an arc lamp actually approaches in quality more nearly to the solar luminous rays than does that of any other artificial illuminant, although if an arc lamp be examined in bright sunlight it will present a yellowish appearance. This is in direct opposition to the generally prevalent idea that the arc light is bluish and even violet, but the illusion only arises from the fact that people rarely see an arc lamp burning except at night-time, and as they have always been accustomed to the decidedly yellow gas, oil, or candle light, they naturally by comparison consider the arc blue. It is a remarkable fact that until about the year 1881 electric lighting was, except in the laboratory, only performed by the agency of the electric arc, a development of the classical experiment made by Davy in 1810, when he employed 2,000 primary cells of a very crude type, which he connected to two pieces of light wood charcoal about an inch long and one-sixth of an inch in diameter. When these 'were brought near each other (within the thirtieth or fortieth part of an inch) a bright spark was produced, and more

than half the volume of the charcoal became ignited to whiteness; and, by withdrawing the points from each other, a constant discharge took place through the heated air in a space equal at least to four inches, producing a most brilliant ascending arch of light, broad and conical in form in the middle.' When any substance was introduced into the arc so produced, 'it became incandescent: platinum melted like wax in the flame of a candle; sapphire, magnesia, lime, and the most refractory substances were fused. Fragments of diamond and granite rapidly disappeared without undergoing any previous fusion.' The arched form taken by the luminous particles of carbon, resulted from the upward rush of the subjacent heated air. Were the carbons placed vertically, instead of horizontally, the particles would be disposed differently, and bear little or no resemblance to an arch. The term arch, in its abbreviated form, arc, is, however, retained as the name of the luminous space between the carbons.

The electric arc can be reproduced by placing in electrical contact two pieces of carbon, either of the gas-retort or of the prepared type, and, after applying to them a potential difference of about 45 volts, drawing them apart for a short distance. Such a potential difference is altogether inadequate to cause a spark to dart across even the shortest air space. When, however, these rods are made to touch, a current is initiated, and, the resistance at the point of contact being somewhat considerable, there is a certain amount of heat developed at that point. If the carbons are kept together the contact surfaces will become more or less incandescent, although the amount of light emitted will be very small, the heated surfaces each serving as a screen to intercept the light of the other. If we, however, separate the carbons, either by automatic or by other means, molecular disintegration and volatilisation of the carbon take place, and the air space is impregnated with so great a quantity of carbon particles raised by the current to a state of incandescence, that the resistance of the space is so far reduced as to allow the current to be maintained by a comparatively feeble electro-motive force. The distance to which the carbons can be separated without absolutely disconnecting the circuit, and so causing the arc to be broken, depends upon the E.M.F. available, and can therefore, within certain limits, be

increased by increasing the number of cells, or the potential difference at the dynamo terminals.

The maintenance of the ends of the carbon rods in a state of incandescence involves a continuous disintegrating effect upon the carbons, as well as a certain amount of consumption by ordinary combustion, some of the particles uniting chemically with the constituents of the atmosphere. The products of combustion are, however, very much smaller in quantity, and therefore less harmful, than those derived from a gas, oil, or candle flame. The two rods are not, with a continuous or direct current, consumed at equal rates, the consumption of the rod connected to the positive pole of the dynamo or battery—and called, therefore, the positive carbon—being approximately twice as much as that of the other or negative carbon; when an alternating current is employed the consumption of both carbons is practically the same, because each becomes in turn the positive.

An arc lamp is an important piece of apparatus, which carries two rods or pencils of carbon, which, before the passage of the current, are placed in contact, but which the current itself in passing must separate, and simultaneously set up between them a path of low resistance, so that the current can continue to flow, and render the ends of the rods incandescent. But in order to maintain the arc it is also essential that some device should be provided for 'feeding' the carbons together at a rate proportionate to their consumption. It is obvious that in order to maintain this cycle of changes a greater or less amount of mechanism is necessary. Before, however, we can study this mechanism, some attention must be bestowed upon one or two other important considerations.

One very interesting and striking feature is the difference of formation given to the carbon rods. The end of the positive rod, whatever may be its initial shape or form, becomes in a short time (see fig. 276) worn down to a somewhat conical form, the apex of the cone being, however, absent, and the carbon hollowed out so as to form a kind of crater; and it is in the hollow of this crater that the most intense heat is developed, constituting it, therefore, the chief source of light. The negative rod is gradually consumed until its extremity is of a fairly true conical shape, but

somewhat sharper than the positive carbon, and it is interesting to observe that some of the particles of which the positive rod is denuded are condensed upon the surface of the negative rod. If after being allowed to burn for a sufficient time with a direct current so as to form a crater, the direction of the current were reversed, this crater would be gradually destroyed and another formed on the other carbon. We can readily understand, therefore, that when the current rapidly alternates in direction both the carbons will be similarly tapered.

FIG. 276.

If the hot crater is examined through a sheet of blue glass, it will be seen that it is by far the most intensely luminous, and therefore the most intensely heated, portion of the arc. So great is the difference between the temperatures of the two carbons that while the negative ceases to be luminous almost immediately after the current has been switched off, the positive in the region of the crater remains white- or red-hot for some considerable time. When this carbon has cooled down so that it may be handled without inconvenience, it will be seen that the crater is not only very clearly defined, but that its surface presents a smooth and somewhat metallic appearance, and would seem to warrant the assumption that the exceedingly obdurate carbon, which has never been seen in the liquid state, has been actually fused and re-solidified.

It has been estimated that while 85 per cent. of the light is derived from the positive carbon, only 10 per cent. comes from the negative carbon, the remaining 5 per cent. being attributed to the 'flame,' or the illuminated particles between the two carbons. Some rough idea of the relative thermal intensities of the various parts of the arc may be gathered from these figures, and it is not unusual to speak of the temperature attained by the negative carbon as being largely due to its undergoing a 'roasting' process in front of the still hotter positive carbon. The actual temperature attained

by the two carbons is to a great extent a matter of conjecture. If the substance had ever, under any other circumstances, been liquefied or volatilised, the question would have been rendered much easier, for then we should in all probability have known the temperature at which the change from the solid or liquid state takes place, and we should therefore have known the limiting temperature to which the crater of the positive carbon could be raised. We shall have occasion to again refer to this point, but it may here be observed that experiment would appear to indicate that the temperature attained by the positive carbon is about 3,500° C., the temperature of the negative being somewhere between 2,100° and 2,500° C.

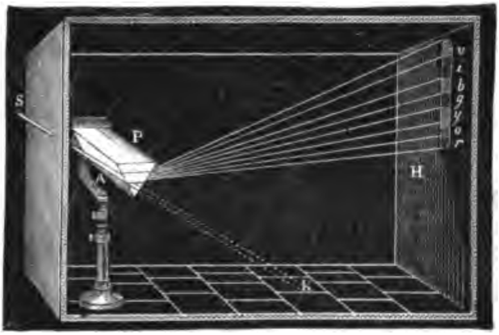
It is a matter of common knowledge that all bodies on being raised to the same temperature become equally luminous, and that a given luminosity results from, or is dependent upon, a definite temperature. It follows from this that if, on different occasions, a carbon rod were raised to the same luminosity, it would be at the same temperature, and, *vice versâ*, if it were raised to the same temperature on different occasions, the light emitted in each case would be of the same intensity.

For the sake of those of our readers who are not acquainted with the character of a beam of light, a few words on the subject may not be out of place. Pure white light is in reality composed of rays of seven different colours superposed upon one another, or blended together. These colours are red, orange, yellow, green, blue, indigo, and violet, and it is by the simultaneous reception of these rays, in certain definite proportions, by the optic nerves, that the sensation of white light is conveyed to the brain. The generally accepted theory which endeavours to explain the manner in which a beam of light is propagated, is based on the assumption that all interstellar space, and likewise the space between the minute particles of all material bodies, is pervaded by that mysterious medium already referred to as ether.

A body may be said to be a luminous substance when it is a source of light-rays, such as the sun or a candle flame. Now the luminosity of a body is ascribed to an almost infinitely rapid vibration of its molecules ; this vibratory motion is communicated to the ether particles pervading and enveloping the substance, and

is propagated in all directions in the form of spherical wave-motions. The colour of the ray varies with or is determined by the rate of vibration. The velocity with which light travels is about 186,000 miles per second, and it has been calculated that the length of a wave of the extreme red end of the spectrum (that is to say, of a luminous ray having the lowest rate of vibration) is such that 39,000 such waves, placed end to end, would cover only one inch, while 64,631 of the extreme violet waves would be required to span the same distance. It follows that in one second, 464 millions of millions of red waves, and 678 millions of millions of violet waves, enter the eye and strike the optic nerves.

Fig. 277.



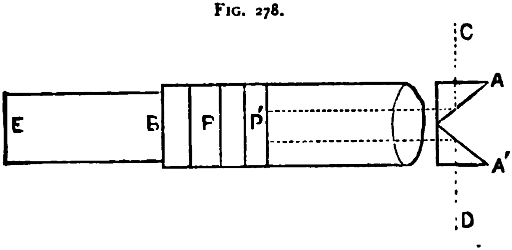
If a beam of solar light (S, fig. 277) is allowed to pass through a hole in the shutter or wall of an otherwise absolutely dark room, it will illuminate a small section of the floor, K, but if a prism or wedge-shaped piece of glass P is placed in the track of the beam of light, after the manner shown in the diagram, the beam will be diverted and the rays separated; on emerging and being allowed to fall upon the screen, H, or even on the wall of the room, the beam will be found to consist of the seven colours above enumerated. This many-coloured band of light is generally referred to as the spectrum.

If a beam be not of a pure white colour, the impurity or irregularity may be due to the chemical constitution of the source of light, or to varying degrees of luminosity. For example, if a beam from a red-hot substance is allowed to fall upon the prism, the decomposition or separation of the rays will not result in the formation of the seven coloured bands, those near the violet end of the spectrum being absent on account of the vibrations being

insufficiently rapid to produce them. When a source of light is heated to different degrees of luminosity, the spectra resulting therefrom will consequently vary, while, on the other hand, if it is raised at different times to the same temperature, and therefore to the same degree of luminosity, the spectra obtained will be identically the same in every case.

A very simple piece of apparatus, called the 'horizontal slit' photometer, has been devised by Dr. Nichols for the purpose of facilitating the simultaneous study of the spectra from two separate sources of light. The instrument is illustrated in fig. 278. It consists of a direct-vision spectroscope with a horizontal slit. Immediately in front of the slit are two 'totally reflecting' prisms A A′. The shape of these prisms is such that the rays from the lamps situate, say, at C and D, instead of passing straight through, are entirely reflected from the inclined faces, the angle which the reflected rays make with these faces being equal to that made by the incident rays.

FIG. 278.

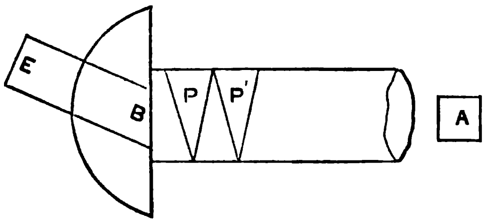


The direction of the two sets of rays is indicated in the figure by the dotted lines. The rays after passing through the slit traverse the dispersing or analysing prisms P, P′, where they are decomposed into their several colours, and the two spectra are projected side by side, and can be viewed together through the eye-piece E, which is furnished for the purpose with a horizontal cross wire and a diaphragm with a narrow rectangular opening. This eyepiece, together with the first joint of the telescope arrangement, is movable about B, the centre of a graduated semicircle, as shown in fig. 279, which is a diagrammatic view taken at an angle of 90° with that shown in fig. 278. Thus the whole range of the spectra can be very conveniently studied.

Now, it has been ascertained that the spectra of the light emitted by the incandescent crater of a pure carbon are always identically the same, that in fact the same proportion between the

various coloured bands is always evidenced, whence it is at once deduced that the temperature of that portion of the fully developed arc is always raised to the same point. This constitutes one great reason for accepting the proposition that the true arc is attained when there is a volatilisation of the carbon; for, so far as experiment has hitherto led us, there is for a given material a constant critical point of temperature at which a change from the solid to the liquid or to the gaseous state ensues, and, the most important point of all, this temperature is not any further increased until the whole of the solid body has been so changed. It will be evident that the admixture with the carbon of any foreign body (all such bodies having a lower critical point of temperature than carbon) must lower the temperature at which volatilisation ensues, and therefore reduce the luminosity of the crater.

FIG. 279.



Moreover, when a body is transformed from the solid to the liquid or gaseous state, a certain amount of heat, known as the latent heat, is absorbed in the process. Thus one pound of ice at the freezing temperature absorbs about as much heat during its conversion into water at the same temperature as would suffice to raise the same mass of water from the freezing temperature to 80° C.; whence the latent heat of water is said to be 80° C. On the other hand, when a liquid is solidified a corresponding amount of heat is given out during the change. Thus one pound of water at the freezing temperature in being converted into ice gives out as much heat as would raise the temperature of the same mass to 80° C.

Again, if we apply heat to water contained in an open vessel, it will be found impossible to raise the temperature above 100° C., any further heat being rendered latent in the steam which escapes. The steam on resuming the liquid state will give up this latent heat. Similarly with the electric arc. There is considerable

resistance at the surface of the carbons, the ends of which are therefore, on being separated, raised to almost a white heat, and, the current being maintained, the temperature of the positive carbon is further raised until the temperature of volatilisation is reached. The vapour consequently absorbs a considerable amount of energy, yielding it up again on re-solidification. The essential point to be noticed is that the temperature of volatilisation having been once attained, no further increase can be made; that is to say, the temperature at which the physical change from the solid to the gaseous state takes place is the limiting temperature to which the carbon can be raised. This means that there is a limit to the intensity of the light which a given pair of carbons can be made to yield. The student must carefully discriminate between the luminous intensity—or, as it is more generally called, the 'intrinsic brilliance'—of the arc, and the quantity of luminous rays which the arc can develop. By the intrinsic brilliance is meant the quantity of light or of luminous rays emitted per square millimetre of crater, and it is this intrinsic brilliance which is limited by the temperature of volatilisation. The total quantity of light emitted by an arc is the product of this intrinsic brilliance into the area of the crater, and it is most important to remember that when the temperature of volatilisation has been reached, any further augmentation in the strength of the current simply results in an increase in the area of the crater, and there is, of course, a proportional increase in the quantity of light emitted. This fact is confirmed by the experiments of M. Violle, who showed that the intrinsic brilliance of the crater remains sensibly constant when the power supplied is raised through a range of 1 to 60, and he also found the intrinsic brilliance of the crater identical for all arcs. The measurements taken in various parts of the spectrum and the photographs obtained 'left no doubt whatever on this point.' The power supplied to the arcs with which he experimented ranged from 10 amperes at 50 volts up to 400 amperes at 85 volts, and it was in this series of experiments that the temperature of volatilisation was estimated to be not less than 3,500° C. The intrinsic brilliance of a fully developed arc has been estimated at 160 candle-power per square millimetre of crater area. According to M. Blondel, who has worked assiduously in striving

to solve many of the problems in arc lighting, the intrinsic brilliance of carbon at 3,500° C. is 8,000 times as great as that of platinum at 1,775° C.

The positive carbon being made hotter than the negative, but yet not exceeding a certain, although imperfectly defined, maximum, warrants the assumption that the negative is never volatilised, and that any diminution which it may suffer must arise from simple combustion consequent upon the combination of the red-hot carbon with atmospheric oxygen. But as there is no free oxygen in the track of the current – that is, along the line joining the two carbons – the combustion takes place around the outer surfaces of the carbon, and this accounts in a great measure for the conical shape assumed by it. To a similar action must also be ascribed the partial tapering of the positive carbon.

Accepting the theory that the carbon is gradually volatilised in the crater, and that there is a certain definite temperature at which this volatilisation takes place, there is also involved the necessity for the expenditure of a certain definite minimum amount of energy, in order that these changes may be brought about. It has been observed that in order to maintain a properly developed arc, a potential difference of about 44 volts between the two carbons is necessary, and it has also been demonstrated that of this amount 38 or 39 volts are lost or expended at or near the surface of the crater, the remaining 5 or 6 volts sufficing to maintain the circuit through the carbon and other vapours between the two rods.

In the present state of our knowledge it is difficult to definitely attribute this sudden fall of potential at the crater to any specific cause, but a number of explanations have been attempted. It is scarcely probable that the phenomenon is due simply to the ordinary resistance at the surface of the carbon, for then it would be difficult to account for the absence of a corresponding resistance at the surface of the negative carbon. There is, however, reason to believe that the fall is due to the volatilisation of the carbon, and that the volts absorbed afford a measure of the energy required in overcoming the molecular attractions or cohesive force of the carbon particles, and it has been supposed that these reactions result in the establishment of a counter electro-motive force in the arc, between the carbon vapour and the positive rod,

amounting to nearly 39 volts. This assumed effect is somewhat analogous to that accounting for the reaction which is set up when a current is sent through a voltameter, and which was fully entered into in the preceding chapter. The effect is also parallel to that remarkable feature in the action of electric motors, viz. the counter E.M.F. which is set up by the armature when it is caused to revolve in an established electro-magnetic field.

When the current is switched off, however, no evidence is obtainable of the existence of any back E.M.F. between the carbons, but these negative results do not give any convincing proof of its non-existence. The gases between the carbons speedily get cool or even displaced, and consequently the carbons are separated by an almost perfect insulator, and, the electrical condition of the carbon vapour being a paramount factor in the question, it follows that the only free portions of such electricity as would flow, did circumstances permit, would be those existing on the electrodes, and these are in any case very trifling. If we were able by some means other than the arc itself to have the two carbons raised to and maintained at temperatures such as they attain in the arc, then we might perhaps obtain some direct proof of the existence or otherwise of this back E.M.F.

The whole question of the existence or otherwise of a counter electro-motive force is, therefore, still shrouded in doubt, but this much is certain, that there is, in a properly developed arc, a fall of potential in the immediate neighbourhood of the crater of about 39 volts, and this fall is independent of the length of the arc, of the area of the crater, and of the true resistance of the various parts of the circuit. It is an interesting fact, and one which has given rise to many different conjectures, that the *apparent* resistance of the arc does not increase proportionally with the distance between the rods. The resistance of an arc of one-tenth of an inch, for example, is nothing like double that of an arc of one-twentieth of an inch. But this is only what should be expected if the theory of volatilisation of the positive carbon is accepted, for however long the arc may be, the volatilisation can only take place in the crater. If, however, the resistance of the air-space with its impregnation of carbon particles, were the only element entering into the question, the resistances in the two cases instanced should

be exactly as two to one. But experiments have been made with arcs of different lengths (the electro-motive force being also varied so as to keep the current strength constant), with the result that, allowing for a definite fall of 39 volts, there remained a resistance which varied proportionally with the length of the arc, and which afforded thereby a demonstration of the actual existence of a sudden drop at this point, which might be due either to the development or existence of a counter E.M.F., or simply to the energy absorbed by the carbon in volatilising.

The great practical lesson to be derived from a knowledge of this effect is that the potential difference which is applied to the lamp must always exceed 39 volts, or it will fail to maintain the arc. It is, in fact usual to provide a potential difference of about 50 volts for each lamp; the actual or true resistance of the arc itself, that is, of the air space separating the carbons when they are in the normal position for lighting, or at a distance of about 3 millimetres apart, being variously estimated at something between one-eighth and one-half of an ohm. Our own experiments tend to show that the latter value is the correct one.

When the potential difference between the carbons falls below 40 volts a steady arc cannot be maintained, and the carbons rise and fall (or 'pump') vigorously—that is to say, the current with the carbons in contact is, consequent upon the reduced resistance, heavy, and the carbons accordingly separate and strike the arc; but the feeble electro-motive force provided is incompetent to cause the all-important volatilisation of the carbon, and the path for the current is wanting in the required amount of carbon vapour. As a consequence, the carbons feed forward rapidly, to be again jerked apart, and, these reactions being continued, we have a variable, hissing, and unsteady arc. Under these circumstances no true crater is completely formed; there is no true volatilisation, and neither of the carbons is raised to its limiting temperature. They are rendered only feebly incandescent, and comparatively little light is emitted.

Letting it be granted that the minimum potential difference required is determined by the temperature of volatilisation, it should be evident that a smaller difference would be sufficient to maintain a given current between any pair of rods, such as iron,

copper, or zinc, which have a lower 'boiling-point' than carbon, and that, as a correspondingly smaller amount of energy is absorbed, the intensity of the light emitted, or the intrinsic brilliance of the arc, should be reduced.

We have, as a matter of fact, demonstrated this point experimentally; for example, two arc lamps were placed in series so that the same current was maintained through them, but one of the lamps had carbon rods, while the other had iron rods of similar dimensions. The illuminating powers were then compared by placing the lamps on opposite sides of the disc of a Hartley's Bunsen photometer. The potential differences absorbed by the respective pairs of rods were measured simultaneously, and it was found, for example, that with a current of 10 amperes and arcs of equal length the carbons absorbed 57 volts, while the iron rods took only 27 volts. A few of the results are appended:—

Current in Amperes	Volts between ends of rods		Distances in centimetres from photometer disc	
	Carbon	Iron	Carbon	Iron
10	57	27	64	31
8·5	55	26	63	32
7·5	53	25	65	30
		Averages		
8·6	55	26	64	31

In each case the arcs were of equal length, about $\frac{3}{16}$ inch. The iron used was soft, and of the same diameter as the carbon. It is interesting to notice that no spluttering was observed in the iron arc after the current became steady, and it will be seen that the potential difference required by the iron arc was only about half that necessary for the ordinary carbon arc, while the illumination was only about one-fourth, clearly showing that the electrode with the higher boiling-point required a higher electro-motive force, and that as the temperature of the electrodes was increased the efficiency of the lamp was enhanced.

Similar experiments were performed with rods of copper, brass, and other metals in place of the carbon, but they all told the

same tale—namely, that the required electro-motive force depends upon the volatilisation temperature or boiling-point of the material of which the electrodes were composed. The experiment with zinc rods was highly entertaining. They spluttered and guttered considerably, although a fairly steady arc was capable of being maintained for a short time. Occasionally the upper rod would penetrate some distance into the lower, the centre of which was simply a mass of molten metal encased in a solid tube, which would ultimately give way some distance down the rod.

When the distance between the carbons is excessive, the end of the lower, or negative, carbon becomes less tapered or conical, and the arc flares and flickers, travelling from side to side across the carbons. There is then a considerable increase in the amount of chemical combustion going on, with the result that the electrical efficiency is reduced and the illumination becomes very variable. When the distance is too small the taper of the negative carbon is lengthened, the illuminating power of the arc is reduced by each carbon acting as a screen for the other, and an unpleasant hissing sound is produced. This shortening of the arc is accompanied by a very imperfect crater of reduced area, and it is only from a portion of this area that the arc is at any one moment passing. To this phenomenon and the consequent varying physical condition of the crater the hissing may perhaps be attributed. When the carbons are too large the current density is proportionally reduced ; the area of the true crater is likewise reduced, and the arc is liable to shift and get out of centre.

The efficiency and reliability of an arc lamp depend very largely upon the quality of the carbons employed. When gas-retort or other irregular carbon is used, the impurities contained therein are fused and give rise to small nodular growths which, under a lens, or even a common magnifying glass, impart to the rods a remarkable appearance, as illustrated in fig. 280. These nodular excrescences do not manifest themselves when properly prepared carbons are employed. Their very presence denotes a wasteful consumption of energy, for they imply that the impurities are, as it were, sorted out from the other constituents of the electrodes ; they are then concentrated and liquefied, and urged across the

arc from one carbon to the other, without emitting that percentage of light rays which would arise were the energy they absorb expended on the carbon. As might have been gathered from what has already been said, these impurities also reduce the efficiency of the arc by hindering the carbon from attaining its maximum temperature.

When the carbons are very porous or wanting in density, the arc is usually lengthened, the carbon disintegrating readily and flaring considerably. With pieces of gas-coke an arc of some inches can be obtained. Mr. Varley introduced at the Inventions Exhibition a lamp with 'flexible' carbons, composed of pieces of charred rope which were coiled up in the lamp, and which were uncoiled as they consumed. In this case the arc was an inch or more in length. This was to some extent an advantage, as only a small percentage of the rays emanating from the crater were intercepted by the negative carbon.

FIG. 280.

The composition of and the method of preparing or manufacturing artificial carbons vary considerably, the precise details being in most cases regarded as trade secrets. Generally, however, graphite derived from gas-retort carbon forms the basis, this being intimately mixed with pure carbon powder derived from the destructive distillation of some such organic substances as gas-tar, pitch, or bitumen. An adhesive substance, such as a syrup of cane-sugar and gum, is then added to make a paste, the rods being shaped either by simply moulding or squeezing, or by forcing the mixture with considerable pressure through a die plate. The latter method is considered to be the more satisfactory. The rods so formed are then baked in an oven a number of times, to decompose the carbonaceous compounds, and drive off the volatile constituents. Immersion in syrup usually takes place between the bakings. But great care is essential to remove any foreign substance from the ingredients, and so to ensure the production of a homogeneous rod.

The chief requirements which it is necessary that a carbon rod should fulfil are that it should be dense, that its molecular or mechanical structure should be uniform, that it should be pure, and that its electrical resistance should be low.

The resistance of prepared carbon varies with the different makers, the resistance of one specimen amounting to 2,430 times that of a similar piece of pure copper, or nearly 4,000 microhms per cubic centimetre. The specific resistance of the comparatively impure and more crystalline gas-retort carbon has been found to be 17 times as great as that of the prepared material. The actual resistance of the prepared carbons ordinarily used for arc lamps is from 0·15 to 0·175 ohm per foot. In order to reduce this they are sometimes coated with a layer of copper deposited electrolytically. But the metallic deposit should be very thin, otherwise it will melt for some distance up the rod, and there will be a danger of fused globules falling off on to the glass globe and fracturing it. It may also be in sufficient quantity to decidedly tinge the flame of the arc with the characteristic green hue of burning copper.

It is obvious that when long carbons are used it is important that the specific resistance should be reduced as much as possible. The resistance of a pair of new carbons has an appreciable effect upon the total resistance of the lamp, and the reduction as the rods burn away tends, under a constant potential difference at the terminals, to increase unduly the strength of the resulting current.

Carbons are frequently 'cored.' There are two ways of doing this; the older process consists in first making the carbon in the form of a tube with a small hole or channel along the axis, and with thick sides, the channel being closed at one end. A solution of certain materials, containing in suspension a fine powder of the same nature as the carbon rod, is then introduced at the free end under high pressure and at a high temperature. The more truly liquid and volatile portions of the solution pass into the pores of the carbon, and are finally more or less evaporated. This solution is intended to displace the air or other gases which are entangled or occluded in the carbon, and which might otherwise make the rod too soft, or wanting in density. The hole

and pores are thus gradually filled with powdered carbon, and ultimately a dense and compact rod is obtained. The core is usually greyer than the rod itself. In the second, or more recent, process, the core is made first and is then placed in a mandril contained in a press, in such a manner that as the mass of carbon paste is pushed along under the action of the plunger, it carries the core, which projects slightly beyond the mandril, with it.

It is customary with direct currents to use a cored carbon for the positive. The core serves the purpose of keeping the crater central, and so conducing considerably towards steadiness in burning. This core is, however, somewhat less luminous than the rest of the carbon, due possibly to the presence of a small quantity of impurity which, volatilising at a lower temperature than carbon, is consequently less heated. Both the carbons in alternate current lamps are cored.

The illuminating power of an arc lamp is a somewhat debateable point, but it may be taken as being very near the truth that the actual power of a so-called 2,000 candle-power arc lamp is equal to that of not more than 875 candles. Assuming a lamp to give a light of 875 candle-power when the current strength is 10 amperes and the E.M.F. 50 volts, it will be evident that this amount of light is produced at a cost of 500 watts, so that were a lamp to consume one electrical horse-power, or 746 watts, it should yield a light of about 1,300 candle-power. Allowing, however, for the various losses in the conversions, it may be taken that on an average circuit the engine indicates one horse-power for each ordinary or 875 candle-power lamp.

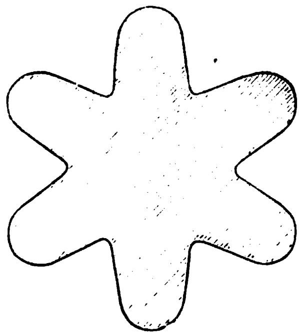
Mr. A. P. Trotter, in a very exhaustive and valuable paper, demonstrates that the distribution of the light rays 'is precisely and identically the same as though the end of the positive carbon were flat. No tilting of an incandescent or other luminous surface can make it brighter; and, on the other hand, if it is covered with a thin imperfectly transparent layer, as in the case of the atmosphere of the sun, the edge will appear less bright than the middle of the disc. The quantity of light emitted by an incandescent disc in any direction is proportional to the amount of surface visible from that direction.' The use of globes considerably reduces the

amount of light actually obtained from a lamp. The proportion of light cut off by globes has been determined to be :—

For clear glass . . .	about 10 per cent.
„ light ground glass . .	„ 30 „
„ heavy „ „ . .	45 to 50 „
„ strong opal „ . .	50 to 60 „

The diameter of the carbon rod varies with the light it is required to give or the current it is required to carry, those most frequently employed ranging from 11 to 13 millimetres in thickness. The lower or negative carbon is, however, in direct current lamps usually thinner than the upper one, the object being to reduce the loss of light due to the screening of the crater.

FIG. 281.



The carbons employed at the South Foreland are fluted instead of being round, the actual shape being illustrated in the cross section shown in fig. 281. Two sizes are used, of 50 and 60 millimetres outside diameter respectively, both being provided with graphite cores. The current employed is an alternating one, and it ranges from 180 to 300 amperes, the variation in the current being made to correspond with alterations in the state of the atmosphere. It was found that with the full current, a 40-millimetre cylindrical carbon became red hot throughout its length; hence the adoption of the fluted carbon, for although the 60-millimetre carbon has a cross section equal to that of a 46-millimetre round carbon, it has a cooling surface 50 per cent. greater, and does not, therefore, get inconveniently hot away from the arc itself. Fluted carbons also assist in keeping the arc central. For purposes of projection the alternating arc is in one sense advantageous in that it projects the majority of its rays horizontally.

The South Foreland arc, when round rods are employed, is unsteady, the carbons burn irregularly, and the embryo craters on the

two carbons are constantly shifting, while there is, with the heavy currents referred to, little or no actual clearance between the carbons. In fact, the arc seems to wander about the ends of the rods, and in so doing to set up a kind of interlocking between the carbons, and to cause therefore a luminosity which varies, in the course of a few minutes, as much as 30 per cent. The photometric readings show that with a current of 240 amperes the luminosity is equal to 16,000 candles.

The experience which has so far been gained with alternating current lamps is not very extensive, but they are usually attended by one serious objection, viz. a remarkable humming sound which is pitched in unison with the rate of reversal in the alternator itself. There can, however, be no doubt that this type of lamp is less efficient than one supplied with a direct current. As has been already pointed out, the alternations prevent the development of a true crater, and consequently there is little or no volatilisation. The virtual E.M.F. necessary for an alternating arc is less than 38 volts, but the actual range is from zero to a maximum of about 50 volts, and there is reason to suppose that it is only during the momentary duration of these higher voltages that there is any effort to raise the carbon to its standard temperature of volatilisation. The light which is obtained is due mainly to the more or less incandescent ends of the carbon rods, both of which are tapered. It must also be noticed that while a large proportion of the rays are directed horizontally, the number of rays projected upwards is equal to the number directed downwards; on the other hand, the distance between the carbons is, in lamps of normal size, greater than with a direct current lamp, so that the screening of one carbon by the other is lessened; it is also lessened in consequence of the more perfect taper of the carbon ends.

The power taken by an ordinary alternating arc with a current of 10 amperes under a pressure of 38 volts is but 380 watts, as compared with 500 watts for the direct current 10-ampere lamp. It is juggling with facts to claim it as an advantage for the alternating current arc that it requires the lower voltage. If we could find a lamp which would require 100 volts in order to yield its maximum intrinsic brilliance, it would be an invaluable discovery

both for series and for parallel working, because the efficiency would be greater and the current which would be taken would be proportionally reduced, the employment of wasteful resistances and choking coils in parallel working being proportionally lessened. During those portions of the cycle of voltage when the pressure is low—lower, in fact, than that required for volatilisation—such light as is developed is due to carbons which are really undergoing a cooling process. In fact, when the illumination obtained is compared with the power expended, the alternate current is less efficient than the direct current.

Mr. Mordey has expressed an opinion that the carbons act as a sort of thermal flywheel, tending to keep up the temperature when the amperes and volts are low. Let it be granted that this is to some extent true, it is equally true that there is a corresponding tendency when the amperes and volts are high to keep the carbons cool. If, therefore, the thermal flywheel be granted a perfect efficiency, then the mean luminosity developed must be considerably lower than that of a 10-ampere direct current lamp. This is very important, because any increase in the amount of energy absorbed results in an increasing addition to the amount of light developed. It would be exceedingly interesting to study an alternating arc in a de-oxygenised atmosphere. Owing to the small amount of volatilisation, and the absence of chemical combustion, the consumption of carbon should be very small.

It has also been urged as one of the advantages pertaining to the alternating arc, that the alternations cause a slight vibration to be set up in the mechanism of the lamp, which tends to assist the feeding of the carbons, but in these days a lamp that requires to be shaken in order to work properly had better be discarded.

The Jablochkoff 'candle' was devised by M. Paul Jablochkoff in 1872, and caused considerable excitement at the Paris Exhibition of 1878. It is perhaps the simplest conceivable form of arc lamp, although, as it is not economical, and as each candle burns for only 90 minutes, it is rarely used. The candle consists of two pencils of prepared carbon about 22 centimetres long and 4 millimetres in diameter, fixed parallel to one another but separated by a strip, 2 millimetres thick, of some fusible non-conducting material such as kaolin. Pieces of split brass

tubing, 5 centimetres long, are placed over the lower ends of the carbon pencils, and serve to form connection with the holder which is attached to the base of the lamp. The upper ends of the pencils are scarfed, and a small lighting fuse consisting of a paste of plumbago and gum serves to connect them together electrically, and affords a path for the initial flow of the current. This fuse is speedily consumed and the arc established. An alternating current is employed, so that the pencils are uniformly consumed, the insulating material also being burnt at the same rate. Owing to the interposition of the insulating strip, that is, to the separation of the carbons, a candle after having been once extinguished cannot be re-ignited unless a fresh lighting fuse is added, or the pencils temporarily connected by a piece of wire, or by another piece of carbon. The lamps are joined in series on a circuit through which a current of eight amperes is sent, the potential difference at the terminals of each lamp being about 42 volts. The rate of consumption of electrical energy is therefore about 336 watts, and this is sufficient to yield, from an open light, a luminosity of rather less than 400 candle-power. It is customary to fix a number of candles, generally four, in a lamp, and consume them in succession.

Another class of arc lamp, called the semi-incandescent, used, however, with a direct current, is typified by the Werdemann lamp, which consists of a large rounded block of carbon connected to the negative lead and supported by a hinged bracket. The positive lead is connected to a thin pointed carbon rod, which, by means of a weight attached to a cord working over a pulley and fastened to its lowered end, is kept in contact with the hinged block. Both carbons become incandescent at, or in the vicinity of, the point of contact. The rod, is of course, somewhat rapidly consumed, and a hole gradually formed in the carbon block, no true arc being developed. Great things were expected of this lamp, but it was very inefficient and is now obsolete.

Our chief object in referring to these lamps is to give some little idea of the channels into which men's minds were directed in their earlier efforts to 'sub-divide' the electric light, or, more correctly speaking, to maintain a number of comparatively small lamps on one circuit.

Coming now to the question of arc lamps in their present state,

it would be convenient if we were able to satisfactorily classify them, or divide them into a few distinctive types, but there is absolutely no simple or natural classification, and a complicated or forced division would be undesirable.

Many efforts have been made to obtain a precise but comprehensive classification, with the result that there are virtually as many classes as there are lamps. It would be possible to divide the lamps into two classes, viz. those used in series or on a circuit through which a *constant current* is sent, and those used in parallel or which have a *constant potential difference* maintained at their terminals, but the difference between them is small, and lamps are now usually so made that they can be placed indifferently on either a series or a parallel circuit. Lamps intended for series working used to be provided with an automatic 'cut-out,' an adjunct which, when the main circuit through the lamp was from any cause interrupted, introduced an alternative path of low resistance, so that the other lamps on the circuit remained unaffected. Break-downs of this character are now, however, very rare, and the cut-out is, except on long circuits, usually dispensed with. Where it is necessary to employ a cut-out the apparatus is generally made separate from the lamp, and is frequently fixed in the plinth of the lamp-post.

A lamp which is intended for simple parallel working might be easily made. In fact, if we suppose the lower carbon to be fixed, and the upper one carried in a sliding holder, which also forms or is continuous with an iron rod of suitable dimensions, then the only other essential is a thick-wire coil which shall, on the passage of the current, be competent to raise the upper carbon just far enough to strike the arc. The attractive power of this coil should be so adjusted that when the arc elongates sufficiently to cause an undue increase in its resistance, and therefore a proportional decrease in the current strength, it should be incompetent to sustain the weight of the core and carbon. These would then fall sufficiently near to the lower carbon to restore the current to its normal strength. This would, however, be now-a-days a rather crude type of lamp, and a somewhat more elaborate design is therefore adopted.

In all cases it is essential that the lamp should automatically

'strike' its own arc, and this action must perforce be controlled by the current—that is to say, the separation of the carbons must always be brought about electrically. In most cases the coil for this purpose is placed in the main circuit, and is usually referred to either as the main or the series coil. When lamps are joined up in parallel, a resistance coil, which is more fully referred to on page 621, is placed in series with each lamp for steadying purposes. To compensate for the loss of power in the 'steadying' resistance, the potential difference provided is higher than that which is provided per lamp when a number are joined in series. In this latter case the extra resistance is unnecessary, because, when the resistance of any one lamp varies, the current strength is not appreciably affected, the other lamps in circuit with it acting as a steadying resistance, and tending to keep the current strength constant.

If the source of light is, for focussing purposes, required to remain stationary—which is, for lighthouse or lantern work, of paramount importance—both carbons must be automatically movable at their respective rates of consumption; but when this is not absolutely necessary, as, for example, in ordinary street or shop lighting, then it is only necessary that one carbon should be fed forward towards the other, which can then be supported in a fixed socket, and gradually burned down. The latter form of lamp is, as a rule, simpler in construction and correspondingly cheaper than the former, or 'focussing,' type, but in this case, too, classification is out of the question, as the one form can be easily converted into the other.

It might be possible to divide lamps into alternating and continuous current lamps, but little if any fundamental difference in the principles of construction is involved. The essential difference is, that with lamps used on alternating-current circuits it is necessary that the cores of the electro-magnets should be short and laminated in order to minimise self-induction and eddy currents, and to enable them to respond quickly to the alternating current.

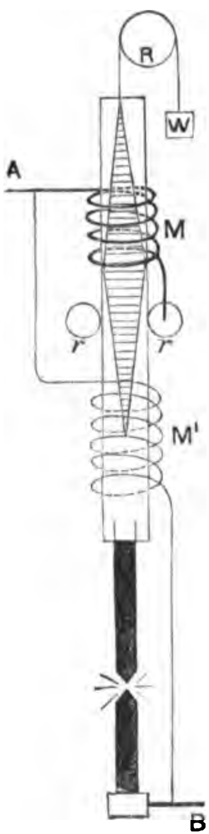
If we attempt to divide lamps in which the 'feeding' forward of one or both of the carbons is controlled mechanically, from those in which the controlling agent is electricity alone, we are

met with another difficulty, for even those in which mechanism is employed for feeding require the intervention of the current to release or start that mechanism. The simplest 'mechanical' lamp would be one in which the upper carbon feeds downwards by gravitation, that is, in virtue of its own weight, when the current passing through the coil used for striking and maintaining the arc is incompetent to overcome this force of gravitation. When, however, such lamps are run in series, and when, therefore, a constant current through each lamp is maintained independently of any variation in the resistance of the arc, it is necessary to provide a second coil, which, by acting in opposition to the striking or series coil, feeds the carbons forward when the length of the arc becomes too great. This second solenoid is joined across the lamp terminals, forming a shunt to the series coil and the arc, and is known as the 'shunt' coil. In some cases the carbons only are shunted, the whole of the current passing through the series coil ; but the object is always the same, viz. to keep the potential difference between the carbons constant. The striking or series coil is of low resistance, while the feeding or shunt coil is of high resistance. As these coils have antagonistic effects, the lamp may be called 'differential.' It is the principle upon which the majority of arc lamps are constructed. Some of these so-called electrically controlled lamps, however, involve delicate mechanical contrivances. To be purely electrical, the moving carbons would require to be perfectly balanced, and only movable under the preponderance of the effect of one coil over that of the other. But no such lamp is now in practical use, so that for this and other specified reasons the division into mechanical and electrical control falls to the ground.

The nearest approach to an electrically controlled lamp is the Pilsen, the only deviation from the principle being the addition of a small weight to the upper carbon holder. The fundamental principle upon which this and other differential arc lamps are constructed is clearly indicated in fig. 282. The current on arriving at A is divided between the two paths, one of low resistance and the other of comparatively high resistance. The former (the main or striking circuit) includes the thick wire coil M, from which the current passes to the contact guide roller *r*, and thence

through the frame to the upper or positive carbon holder, the circuit to B being completed through the arc and lower carbon holder. The other, the shunt or feeding circuit, consists of the coil M^1, which comprises many turns of fine wire, its ends being connected to A and B respectively. These coils are, in the lamp to which the diagram more particularly refers, wound upon a brass tube, inside which another brass tube is loosely fitted, so that it can slide up and down freely. The shape of the soft iron core is like that of two long cones placed base to base; this core is fixed inside the inner tube, and is almost balanced by a weight W attached to a cord passing over the pulley wheel R.

FIG. 282.



When the current is switched on, nearly the whole of it passes through the striking coil M and the carbons, which are then touching one another. The coil consequently exerts a strong attraction upon the core, and raises it slightly, thereby separating the carbons and starting the arc.

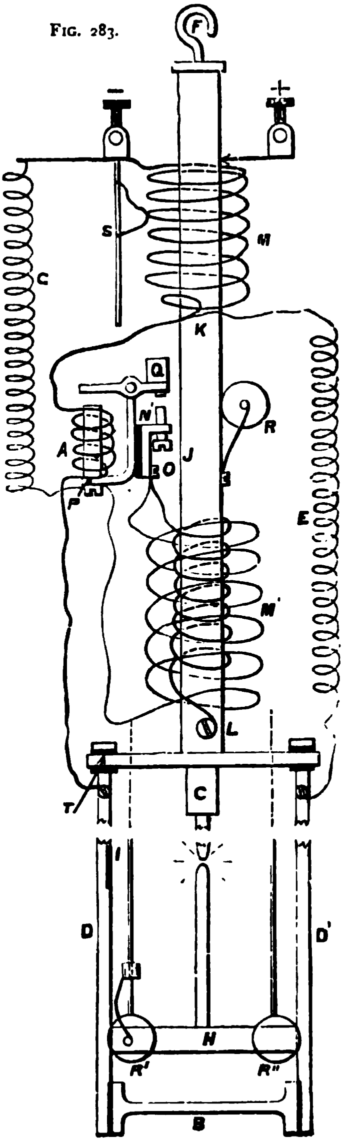
The resistances of the coils M and M^1, and the lengths of the wire with which they are wound, are so adjusted that, the arc having been struck and having arrived at the proper length, their action upon the core is exactly balanced. Any increase in the resistance of the main or series circuit, caused by an increase of the length of the arc, disturbs this balance, increasing the current through the shunt coil, whence the core, with the upper carbon attached, is attracted downwards by the shunt coil, and in descending again restores the balance, re-adjusting the arc to its normal length. It will thus be seen that in the event of a disconnection between the carbons such as might happen before lighting up, the coil M^1 takes the whole of the current, and continues to draw the core down until the two carbons enter into contact.

Immediately this happens a heavy current passes through M at the expense of M^1, and the core and upper rod are raised just sufficiently to establish the arc. The arrangement is very sensitive, and in actual practice the two coils so react one upon the other, that there is no apparent fluctuation in the light, and the two carbons are kept uniformly apart from the first striking of the arc until the current is switched off or the carbons are consumed.

The core in the Pilsen lamp is not made of a simple cylindrical rod of iron, because of the tendency it might then manifest to balance itself, or to take up a position in the middle of the electro-magnetic field produced by the two coils; and although a variation in the magnetisation of either solenoid would move the core away from that position, there would still be a tendency to return to it, and in so doing to cause fluctuations in the arc. By using the conical core this difficulty is overcome, because as the magnetisation by the preponderating solenoid increases, and attracts the iron, it acts upon a gradually increasing core, so situated that it can never get into its 'best position,' but remains steady at any point in a comparatively long range. Fairly satisfactory lamps have, however, been made on similar lines, but with ordinary cylindrical cores.

A detailed diagram of the lamp is given in fig. 283. The lamp case and the tube J are electrically connected to the positive terminal +. From J the current is transmitted by contact rollers R to the inner brass tube C (containing the double conical iron core), and thus through the holder to the positive carbon. Thence it passes through the arc to the negative carbon holder H, and thence again through the contact rollers R′ R″ to the negative guide rods D, D^1, both of which are insulated from the bottom plate of the lamp, as well as from each other at B. The current being thus divided, one part (the lesser) passes through the iron wire resistance coil E, and the greater part through the automatic cut-out coil A, these two branches re-uniting at K, and thence passing through the main coil M to the negative terminal marked −, from which it is carried to the positive terminal of the next lamp in series, or the negative terminal of the dynamo, as the case may be. The negative holder is supported by two cords which pass over pulley wheels and are connected to the brass tube containing the core. This

FIG. 283.



is more clearly indicated in fig. 284, where the cords are shown connected to the rods attached to H, R R′ being the pulley wheels. One of these wheels, R′, has very fine teeth cut round it, into which the click, which is to be seen above the wheel, engages, so as to allow the wheel to rotate freely for feeding, but at the same time to prevent it moving in the reverse direction. The cord, therefore, during the separation of the carbons has to *slide* along the groove, sufficient friction being in that way introduced to prevent sudden or jerky separations.

The positive holder is usually about $1\frac{1}{2}$ ounce heavier than the negative, so that when no current is flowing the carbons run together.

The action of the series current then is to draw the iron core, to which the positive carbon is attached, up into the coil M, and thus to strike the arc. The shunt circuit passes from the screw L (fig. 283), round a solenoid of stout copper wire, to the insulated bracket O, and returning from thence through the shunt-coil proper, M^1, which consists of many turns of fine copper wire (wound in the same direction as the spiral of L), having its other end attached to the bracket P of the automatic cut-out, from whence it

passes through a coil of stout German-silver wire G to the terminal marked —. The number of convolutions of the coil M[1] and their resistance are so proportioned that (when the arc has been drawn to a length of about $\frac{1}{8}$ inch) the attractive action counterbalances that of the main coil M and the small extra weight of the positive holder. Equilibrium being thus established, the arc is maintained at its normal length and resistance so long as the current is kept constant. If from any accidental cause (such as the fracture of a carbon, mechanical injury, or the breakage of a cord) the main current cannot flow from C to D and D[1], then the magnet A of the automatic cut-out fails to hold down its armature, which by reason of the weight on its unattracted end falls in the opposite direction, and establishes a contact with the screw N on the insulated bracket O, thus opening a path for the main current *viâ* L, O, N, Q, and G to the lamp terminal marked —, and so preventing a complete disconnection or the destruction of the shunt-coil M[1].

The negative guide rod D is fitted with a strip of ivory I, so situated that when the carbons are nearly burnt out, the contact roller R[1] ceases to make contact, the current ceases to flow round the magnet A, Q falls, and the lamp is cut out of circuit. The function of the alternative path from R″ through D[1] and of the iron resistance E is that, when the lamp is burning, the resistance E causes the greater part of the current to pass *viâ* D, thus securing the efficient action of the magnet A and preventing the lamp being prematurely cut out. When, owing to exhausted carbons, the lamp is in process of cutting out naturally, the contact roller R[1] in passing from D on to the insulated strip I would carry an arc after it from R[1] to D, were it not for the temporary path afforded from D[1] through E, until such time as the main current has been diverted through the path L, O, N, Q, G. The German-silver coil, G, has no action upon the working of the lamp; it is a compact form of resistance, equivalent to the apparent resistance of the lamp, to be thrown into the main circuit, when the lamp is cut out automatically; it is superfluous with a self-regulating series dynamo.

A view of the interior of the lamp is given in fig. 284, in which the lettering corresponds to that employed in the diagram, fig. 283.

Fig. 284.

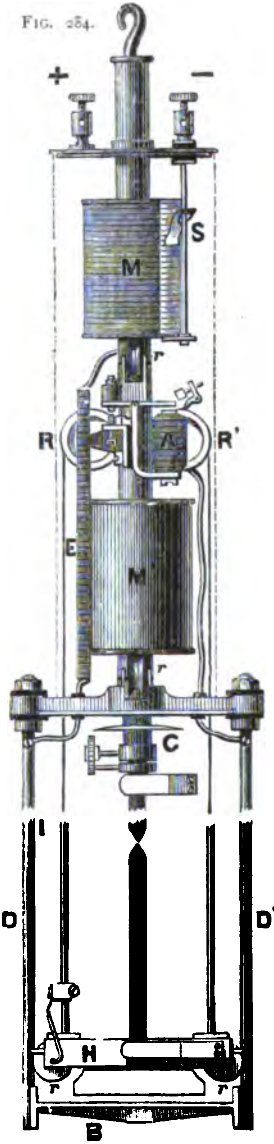
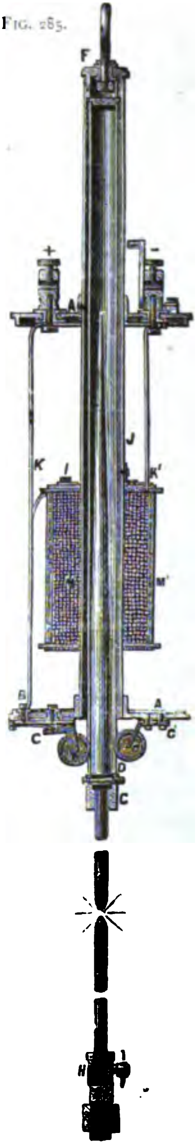


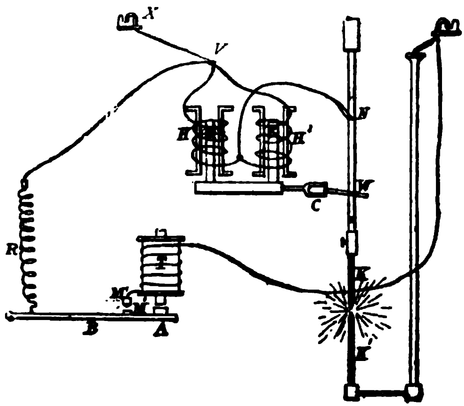
Fig. 285.



It will be observed that a means of final adjustment is provided by the movable contact S, which can be used to cut out one or more of the convolutions of the main coil M. The friction roller is here lettered *r*, and, as already mentioned, R R′ represent the pulley-wheels over which the cords connecting the positive and negative holders together are passed.

A sectional view of another form of lamp is given in fig. 285, in which the two coils M and M[1] are wound on the same bobbin, but in opposite directions. The long conical core is clearly shown at D. The negative holder is suspended in the same way as in the bi-conical form, but the pulleys and other parts, such as the cut-out, are not shown in this figure.

FIG. 286.



Another very simple and efficient lamp, originally designed for use on a constant current or series circuit, is that invented by Mr. C. F. Brush. It was one of the first, and it certainly remains one of the best, of modern arc lamps. A great feature in its favour is the extreme simplicity of the mechanical contrivance. The principle is illustrated in fig. 286. The terminals X Y usually take the form of a pair of brass hooks which, by being dropped over horizontal pins on the under side of a suspending board, place the lamp at once in the main circuit. The negative carbon K′ is fixed, and, being gradually consumed, the arc is steadily lowered in position, the upper or positive carbon, K, falling at a corresponding rate.

The current enters the lamp at the positive terminal X, and divides at V in the main circuit, passing through the low resistance coils H H′, in parallel, in such a way as to generate powerful but opposite poles at the lower ends of the solenoids. On leaving the

coils the currents re-unite, and, passing by a wire to the upper carbon holder N, traverse both carbons, the lower of which is connected to the negative terminal Y. The shunt circuit, the resistance of which is 40 ohms, is made by a thin wire, not shown in the diagram, passing from X round the bobbins H H′ in series, then round the 'cut-out' bobbin T, from which it passes direct to the terminal Y. The thin coil on H H′ is wound outside the main coil. Connection is also made between V and the pivoted lever E, by means of a wire and resistance spiral R, but this will be again referred to presently.

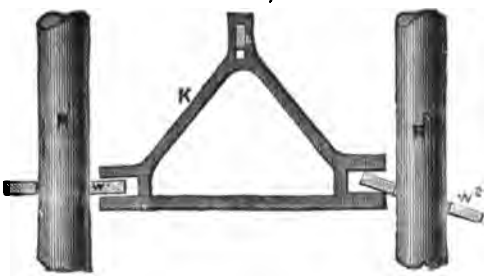
Assuming the carbons K K′ to be in contact, the passage of the main current through the coils H H′ causes the soft iron cores N S and their horizontal yoke-piece to be drawn upwards. The yoke-piece is provided with a fork C, which tilts a washer-clutch W, causing it to seize the carbon holder and raise it sufficiently to strike the arc. Under normal conditions only about 1 per cent. of the total current passes through the shunt coils, but when the arc increases in length, and thereby raises the resistance of the main circuit, a proportionally larger current passes through the long thin wire coils on H H′. Being wound in the opposite direction to the few turns of the main coils, the shunt-coils cause a diminution of the magnetisation of the cores or plungers N S, which therefore fall, and, causing the clutch W to loosen its grip of the holder, allow the positive carbon to fall, by the force of gravitation, until the length of the arc is so far reduced as to re-establish the normal division of the current through the main and shunt coils. We see, then, that the function of the thick wire coil is to tilt the clutch and strike the arc, while that of the shunt coil is to level the clutch, allowing the rod to slide and feed the carbon downwards. As a rule, these reactions take place so gradually that the upper carbon is maintained at a uniform distance from the lower, and is simply fed at a rate corresponding with the consumption.

The cut-out coil T performs a useful function on a constant current circuit. It will be remembered that the shunt circuit includes a coil of many turns of thin wire on the bobbin, T. Now when the main circuit is broken, the whole current of undiminished strength has to pass through the shunt circuit, and might soon

destroy it; but the coil T is so adjusted that when this increased current passes through it, its core becomes sufficiently magnetised to raise the armature A, and with it the lever B. This lever carries the small contact stud M, and this on rising makes contact with another stud M′, which is connected to a short thick wire coil wound round T, the other end of which is connected to Y. It follows that under such circumstances a low resistance circuit is established from V, along R, and B, to M, and so on to Y.

Of course as the main or striking circuit is disconnected, the positive carbon holder is not interfered with by the clutch, and can therefore, if only a portion of the carbon has been broken off, descend and re-establish the arc, when the current flowing through the thick coil on T will be diminished and the cut-out circuit disconnected.

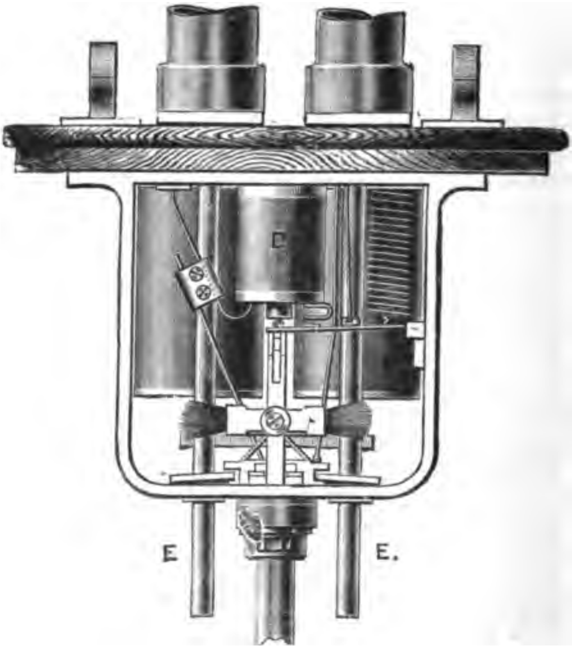
FIG. 287.



Usually the Brush carbons are a foot long and last for eight hours or thereabouts. When a longer period of lighting is likely to be required, lamps with two pairs of carbons are employed. The device for 'changing-over' from one pair to the other is purely mechanical and is illustrated in fig. 287. The positive carbon holders R^1 and R^2 are parallel one to the other, and each is furnished with a washer clutch, as shown at W^1 and W^2. These clutches are operated by a small frame K, which is supported by the lever (shown in section at L) attached to the plunger or soft iron core of the striking and feeding solenoids. By the simple device of making one of the forks in the frame K a trifle higher than the other, this higher fork tilts its clutch before the other begins to act, and consequently lifts its corresponding carbon holder a greater distance than does the other. At the moment when the first carbon holder R^2 is raised, the path through it is short-circuited by the circuit through R^1, and consequently there

is no effort to establish an arc from the carbon attached to R^2. The next moment, however, R^1 is also raised, and the arc then establishes itself from the carbon carried by this holder, and in all subsequent feeding and controlling movements the pair of carbons across which the arc was first started are alone affected, because, although both positive carbons are raised and lowered together, the ends of the reserve carbons never come into contact, and the

FIG. 288.

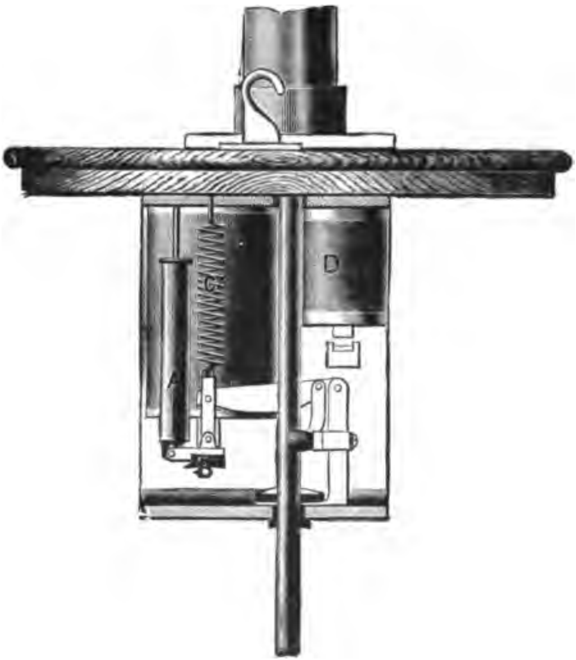


potential difference is insufficient to start an arc across the air space which separates them. When the one pair of carbons have been so far consumed that they cannot meet when the frame falls, the circuit is completed through the reserve carbons, and their arc established, after which it is maintained by the same apparatus acting in the same way as with the first pair.

Figs. 288 and 289 are two views of a 'double-carbon' Brush

lamp at right angles one to the other. The positive carbon holders E E', which are hollow, are filled with glycerine, and work in larger tubes extending above the lamp, portions of these tubes being shown in the figures. A long plunger is fixed to the upper end of each tube, so that as the holder rises the plunger has to pass through the glycerine. This arrangement, which has for its object the prevention of any sudden or violent movement

FIG. 289.



of the carbons, is technically known as a dashpot. D is the short-circuiting or cut-out coil, and (in fig. 288) the pair of striking and feeding coils is clearly shown. Another dashpot, A, fig. 289, is fitted to check the motion of the clutch, which is also provided with a regulating spring C. Electrical contact is made between the striking coils and the carbon holders (corresponding to the contact at N, fig. 286) by means of fine wire brushes.

Figs. 290, 291, and 292 illustrate a more recent form of Brush clutch. The carbon-holder A is provided with a long saddle-shaped slide D, carrying on the rivet *d* a friction-block C. This block is raised or lowered and simultaneously moved forward or backward by the lever B, which is loosely pivoted at *b*, and which in its turn is moved by the arm F attached to the armature of the striking coils. In fig. 290, the arm F is raised, and B has moved

FIG. 290.

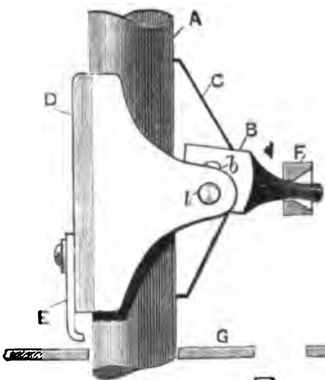
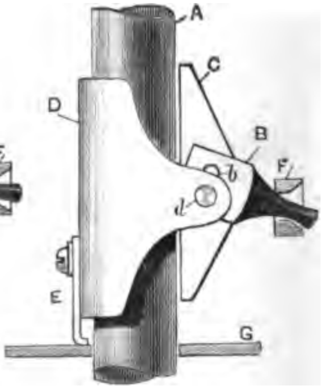


FIG. 291.



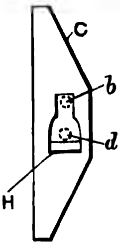


FIG. 292

C forward, pressing it against A, and, D being also raised, A is lifted and the arc struck. As the carbon burns away the clutch falls with it until the clutch trip E strikes G, the bottom plate of the lamp (see fig. 291). F continues to fall, and consequently C is tilted away from A, which then falls through until the normal current strength has been re-established ; F is then promptly raised again. These actions depend on the slotted hole H (fig. 292)

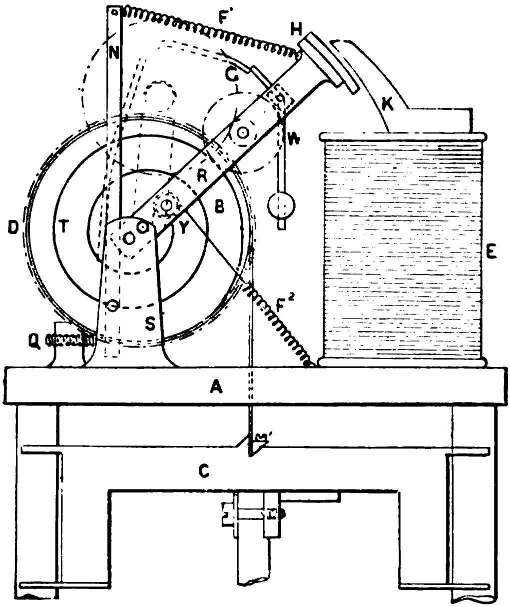
being kept free from dirt. The clearance for the lower pivot *d* is about $\frac{1}{16}$ of an inch, and is useful in allowing C to be readily removed from A when E strikes the plate G. The advantages claimed for this clutch are the promptness of its action, its unusually large gripping surface, that its action cannot be impaired by slight irregularities in the surface of A, and that dashpots are dispensed with.

FIG. 293.

The Brockie-Pell arc lamp is illustrated in fig. 293; the main and shunt coils are wound on separate bobbins fixed parallel to one another. The two cores pass through the ends of, and operate, a 'see saw' lever which is pivoted at its centre. The two carbon holders are connected by a cord passing over a pulley wheel pivoted on the base of the lamp-case. The upper or positive holder is provided with a rack-rod which gears into a pinion; the spindle of this pinion works in the frame of the lamp, and carries a comparatively large wheel having a strong broad rim, against which a brake in the form of a small leather roller is applied. The lever carrying this brake turns on a weighted sector-shaped lever, which is loosely pivoted but moves solidly with the brake wheel, its descent being, however, limited by a stop; the outer end of the brake-lever is connected with the link supported by the see-saw lever. On the passage of the current the striking coil raises its end of the lever, applies the brake to the wheel, and raises the positive carbon, the negative carbon being caused to recede at the same time. The arc is therefore established. As the arc lengthens and the main current diminishes, the shunt current increases and the other end of the see-

saw lever is elevated; consequently the brake lever is depressed, the brake wheel released, and the carbons allowed to feed together. These reactions take place readily, the feed being practically continuous, and a steady light can be maintained even with a variation in the main current of 20 per cent. above or below the normal working current. The initial adjustment for balancing the carbon holders to operate with any particular strength is effected by means of weights. As compared with the majority of lamps, the

FIG. 294.

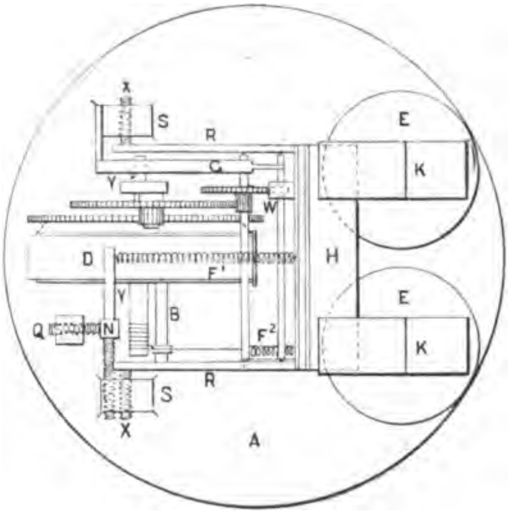


mechanism is simple and the workmanship good, two facts which account for its successful working.

The Siemens 'Band' arc lamp is also extensively employed, and shares the bulk of the existing work with the Brockie-Pell and Brush lamps. Its mechanism is remarkably compact, and it is therefore shorter than most lamps. Figs. 294 and 295 give details in plan and elevation of the regulating mechanism, the lettering in the two figures being identical.

The frame C, which carries the upper positive carbon of the lamp, is suspended by a conducting metal 'band' wound round the circumference of the barrel D mounted on a horizontal axis Y, and containing a volute or coiled spring T, so arranged that the weight of the positive carbon and its frame tends to rotate the barrel in opposition to the spring. The barrel carries a toothed wheel which is connected by a train of wheels to an escapement and pendulum W, whereby the rotation of the barrel, and consequently the descent of the positive carbon due to gravity, is allowed

FIG. 295.



to take place at a slow regulated speed. The barrel D with its wheelwork and escapement is mounted in a frame R, pivoted at its lower end at a point X near the axis of the barrel Y, to standards S projecting up from the lamp-base A. The upper end of the frame carries an armature H facing the pole-pieces K of an electro-magnet E, which is connected as a shunt across the terminals of the lamp. When the electro-magnet attracts the armature it draws the frame R downwards about its pivots, and thus lowers the barrel carried by it, and also the positive carbon

with its frame C. The frame R is held back at its upper end by a spring F^1 (adjustable by a set-screw Q acting on the lever N), the tension of which is regulated to withstand the pull of the electro-magnet with more or less force, and which, when no current is passing through the electro-magnet, holds the frame R in such a raised position that the movement of the escapement is arrested by the stop G. When the frame R is in this position, and the positive carbon is thus raised to such a distance from the lower or negative carbon that no arc is formed, the relatively strong current passing through the coils of the electro-magnet E attracts the armature H, thus lowering the positive carbon until the escapement is freed from the stop G, whereupon the positive carbon and its frame C will be free to descend by gravity until it comes in contact with the negative carbon. Owing to the passage of the current through the carbons, the current through the electro-magnet E will be weakened to such an extent as to allow the spring F^1 to raise the frame R again, so as to arrest the escapement and raise the positive carbon sufficiently to strike the arc. A position of equilibrium is thus established by the increase of the resistance of the arc, and sufficient current passes through the shunt to cause the electro-magnet E to balance the pull of the spring F^1. It will here be observed that normally the carbons are apart when the current is switched on, and that prior to the starting or striking of the arc the shunt coil is required to cause the positive carbon to descend upon the negative. It will also be seen that under these circumstances a series or striking coil is unnecessary.

As the positive carbon burns away, and the resistance of the arc increases beyond this point, the attraction of the electro-magnet E overcomes the force of the spring F^1 and the frame R is attracted, whereby the escapement W is released from the fixed stop G, and the frame C is lowered, partly by the descent of the axis of the barrel D and partly by the rotation of the barrel on its axis Y. When the resistance of the arc is thus lessened the electro-magnet becomes correspondingly weakened, and the frame R is raised again, by the spring F^1 lifting the positive carbon frame C and engaging the escapement with the stop G. In this manner the normal resistance of the arc is re-established, and

the regulation of the positive carbon is governed according to the variation in the resistance of the arc itself. When introducing fresh carbons, the upper carbon frame C is raised by hand, whereupon the volute spring in the barrel is enabled by uncoiling to turn the barrel so as to wind up the suspension band again, the train of wheels being so arranged that this can be done more or less rapidly without actuating the escapement. To compensate for the variation in weight of the positive carbon in burning away, a helical spring F^2 strains a cord which is led over a pulley B on the frame R, and becomes wound on the axis Y of the barrel as the barrel revolves, lowering the positive carbon so as to exert more and more downward pull on the frame R the more the carbon is consumed. Thus the spring being stretched to the least extent when the carbon has been freshly introduced, its tension, and consequently its downward pull upon the frame R, will increase as the weight of the carbon decreases.

The negative carbon is placed in a holder at the bottom of the lamp frame, and is therefore fixed in position, so that, like the Brush, it is a non-focussing lamp.

The Siemens Band lamp is thus remarkable in that the adjustment of the length of the arc is controlled entirely by the shunt-coil, which acts in proportion to the current passing through it. It nevertheless burns with great steadiness, the upper carbon feeding downwards with that steady and imperceptible motion characteristic of a good lamp.

The Crompton-Pochin arc lamp is of the differential type, the coils acting by means of a lever on a brake wheel and pinion gearing into a rack-rod which carries the positive carbon.

Figs. 296 and 297 are vertical sections of the lamp at right angles one with the other. The main or series coil M and the shunt-coil S are provided with soft iron cores C_1, C_2, the lower ends of which articulate with the pivoted lever L. This lever, by means of the brake B, releases or holds the escape wheels B W, and with them the rack-rod. On completing the circuit, the current enters at the positive terminal P, passes through the series coil M to the frame of the lamp, and thence through the two carbons and up the insulated guide-rods to the negative terminal N. The current, in passing through M, lifts the core C_1, and with it the lever L. The

escape wheels and rack-rod are thereby raised and the arc is struck. As the carbons burn away and the arc lengthens, the action of the coil S, which is coupled in shunt across the arc, increases, until, finally, the lever L is depressed sufficiently to allow the weight of the rack-rod to be supported by the feed pin (F, fig. 298), instead of by the brake and wheels, which are thus free to revolve and to feed the carbons together. An air dashpot, D, is provided to prevent any sudden kick, and is so arranged that, although the carbons cannot be pulled apart quickly, their motion is not retarded in the opposite direction. The dashpot being inverted, cannot be affected by dust, &c., and can be easily removed for cleaning. The prompt action of the coils causes the carbons to approach one another by imperceptible movements. The skeleton diagram, fig. 298, is added to illustrate more clearly the action of the lamp and the circuit through it. It will be noticed that the coil, S, is simply a shunt across the arc, the whole of the current passing through the series coil M.

FIG. 296.

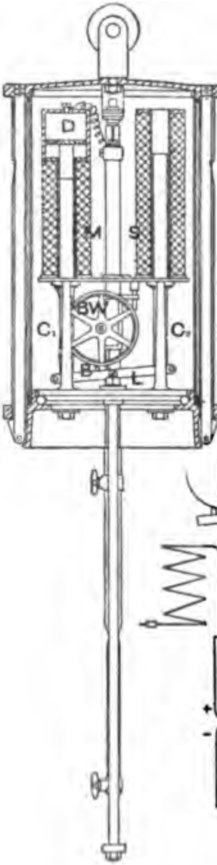
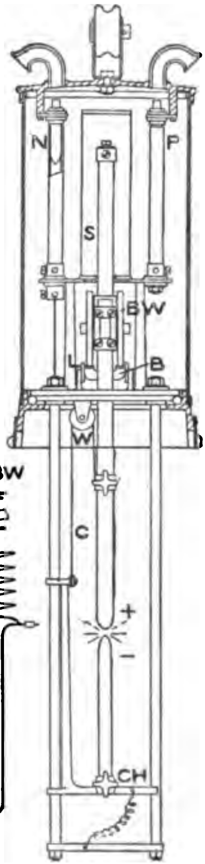


FIG. 297.



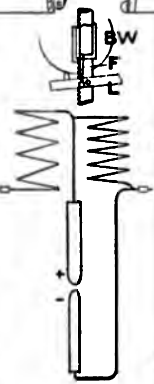
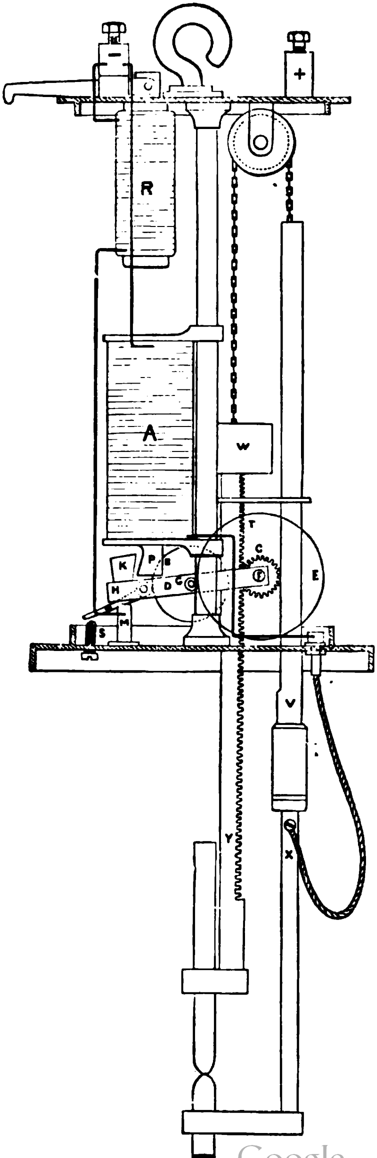


FIG. 298.

The case of the lamp is insulated from the mechanism by a ring of non-conducting material; and, in order to give additional security in handling, the act of opening the lamp disconnects it from the circuit by means of the plug sockets. The lamps are made for either parallel or series circuits, but when they are to be run in series an independent cut-out is provided.

The Phœnix arc lamp is also differentially wound. Its construction is illustrated in fig. 299, where A represents an electromagnet wound with two coils, the pole-piece, P, of which acts upon an armature, K, fastened upon a frame, H D, pivoted at F. This frame also carries a brake wheel B, on the axle of which is fastened a small pinion G, and brake lever N made to grip B by a helical spring wound round the axis, by which it is attached to the frame H D. The pinion G gears into the larger toothed wheel E, on the axis of which is another pinion, C, engaging with the rack R of the positive carbon rod. This rod carries a weight W, which enables it in descending to lift the negative rod V X. When no current is flowing the brake lever N

FIG. 299.



rests on the screws, which releases the brake wheel and allows the carbons to come into contact. The current enters at the positive terminal on the right hand of the figure, passes through the framework of the lamp to the rod Y, and thence to the positive carbon. It returns from the negative carbon by the insulated rod X and flexible wire attached to it, passing through the thick wire coil on A, and from this to the negative terminal. The magnet attracts K, raising the frame H D, thus causing the lever N to grip the brake wheel and, by turning E and C, to raise Y and lower X for the purpose of separating the carbons and striking the arc. As the carbons burn away the difference of potential at the terminals rises and the current in the fine wire coil round A, which is connected as a shunt to the lamp terminals, increases. This weakens the electro-magnet A, and allows the frame H D to fall and the carbons to approach. When the lever N comes in contact with the screw S, the brake is released, allowing the carbons to approach as the consumption continues. If the carbons burn out, or if from any other cause the circuit through them is broken, the frame H D drops on the contact pillar M; this completes the circuit from the lamp frame through the German-silver resistance R to the negative terminal, thus forming the cut-out and preventing a break in the continuity of the circuit.

The resistance of the coils and the carbons in an arc lamp causes, naturally, a certain loss of potential consequent on the passage of the current through them. This loss is usually about 5 volts. Hence, although a good 10-ampere arc can be maintained with a pressure across the arc itself of 44 or 45 volts, as much as 50 volts require to be applied to the lamp terminals. The current being 10 amperes, it follows that the power absorbed in the lamp is 500 watts, and the candle-power being about 850, it follows also that we have 1·7 candle per watt. This ratio we may call the efficiency of the lamp. Larger lamps, or lamps with larger carbons taking heavier currents, have a higher efficiency even than this. The 13-mm. carbon offers a resistance of 0·175 ohm per foot, whence with a 10-ampere current the fall of potential in that length of carbon is 1·75 volt. If now we suppose the foot of carbon to have been consumed and the pressure of 50 volts still maintained, then the energy previously expended upon the carbon is

available for the other portions of the lamp circuit. The resistance is, in fact, materially reduced, and the result is that there is a proportional increase in the strength of the current or in the length of the arc.

Again, it should be remembered that there is frequently a slight variation in the condition and resistance of the arc itself, but it is very desirable that the current in practical working should be kept as uniform as possible. Variations of resistance we must have, so, in order to make those variations of minimum effect, it is the practice when lamps are run off a pair of mains at a constant potential difference, to work with a higher pressure than 50 volts, and to insert resistance coils capable of absorbing the excessive volts. For example, it is frequently the practice to place the lamp across a pair of conductors having a potential difference of 65 volts, or 15 volts more than is necessary for the lamp. This means that a coil of wire, say of iron, has to be used ; it must be large enough to carry a current of 10 amperes, and must therefore offer a resistance of $r = \frac{e}{C} = \frac{15}{10} = 1 \cdot 5$ ohm. The function of the added resistance is to keep the total resistance of the particular lamp circuit more nearly uniform, and therefore by maintaining a practically uniform potential difference between the carbons, to steady the light. This method is somewhat costly, for instead of taking $E \times C = 50 \times 10 = 500$ watts, the absorption of power is increased to $(50 + 15) \times 10 = 650$ watts, or an increase of 30 per cent., while the efficiency is reduced to 1·3 candle-power per watt. It is far preferable, where it can be done, to employ a pair of mains with a potential difference of, say, 110 volts, and join two arc lamps in series between them. The lamps taking 100 volts, there remain only 10 volts to be absorbed by the steadying resistances. But the length of this coil of wire is considerably reduced, for having now to absorb only 10 volts, this can be done with a resistance of $r = \frac{e}{C} = \frac{10}{10} = 1$ ohm. This will absorb $e \times C = 10 \times 10 = 100$ watts, and the lamps together with the resistance will absorb $110 \times 10 = 1{,}100$ watts, or an increase of 10 per cent. upon the power actually absorbed in the two lamps. The gain is obvious. With really first-class lamps it is, however, possible to join two

lamps in series on a 100-volt circuit without any steadying resistance at all. In that case the resistance of one lamp is relied upon to reduce the otherwise baneful effects of a variation in the resistance of the other lamp. Where a larger number of lamps are joined in series, there is manifestly no necessity for any added resistance.

When alternating current lamps are run in parallel, a 'choking coil' takes the place of the comparatively high resistance coil employed with the direct current. The choking coil was referred to in Chapter XIII., and it will be remembered that it consists of an iron core with a comparatively few turns of thick copper wire round it. The combination offers an inappreciable resistance, but it has considerable and self induction, which causes the current to lag behind the E.M.F., and so enables a fall of pressure to be obtained with a comparatively small absorption of power. Consequently, any variation in the pressure between the carbon points becomes a smaller proportion of the total pressure, and has therefore less effect than would be the case in the absence of the choking coil.

Apart from the cost of the power required by an arc lamp, there are also to be considered the cost of the carbon rods and of the necessary labour involved in 'trimming.' A good steady arc maintained between 13-millimetre carbons with a current strength of 10 amperes will consume about 1·5 inch per hour. For example, we may mention that in one set of tests with six 10-ampere lamps, using 13-millimetre carbons, the positive being cored and the negative solid, we obtained the following as the result of 11 hours' running :

Lamp	Carbon consumed in 11 hours		Consumption per hour		
	Positive	Negative	Positive	Negative	Total
	inches	inches	inch	inch	inch
A	11·125	5·500	1·011	0·500	1·511
B	10·812	5·500	0·983	0·500	1·483
C	10·250	5·500	0·932	0·500	1·432
D	10·125	5·125	0·920	0·466	1·386
E	10·615	5·100	0·965	0·461	1·426
F	10·250	5·000	0·932	0·454	1·386

According to Mr. Louis B. Marks, the life of a carbon varies with a current of given strength directly with its diameter and inversely with its resistance. Thus the life of a 1-in. Brush carbon having an actual diameter of ·986 in. and a resistance of ·061 ohm is, according to his test, 26·15 hours. According to the law above stated, the life of a ⅝-in. Brush carbon having an actual diameter of ·618 in. and a resistance of ·0735 ohm would be by calculation 13·62 hours. When put to test this carbon burned 13·64 hours. It is hardly within our province to enter here into the cost of the various items and materials used in electric lighting, but it will be evident that there is in every lamp a certain amount of waste. Enough carbon must in the first place be inserted in the holder to ensure sufficient contact; this is waste. The carbon cannot be burned nearer than within say half-an-inch of the holder; this also represents waste. It is, moreover, all but impossible to gauge the actual time during which a lamp is required to burn on any particular occasion. Hence, if in trimming, the carbon is found to be within an inch or two of the holder, it must be removed and a new carbon substituted; this is more waste. Altogether on an installation comprising a number of arc lamps the carbon wasted may easily amount to some thousands of feet in the course of a year. One way of reducing this loss is to employ double carbon lamps, or lamps which carry two pairs of carbons. One pair, as was shown in describing the Brush lamp, is (automatically) lighted first and, after having burned down to within a small but certain pre-determined distance from the holders, the current is automatically diverted and made to pass through the other pair. This reduces the waste to a minimum, but it means that extra complications must be introduced into the lamp, possibly at the cost of reliability, and it is a device which is not resorted to unless really necessary.

CHAPTER XVI.

INCANDESCENT LAMPS—PHOTOMETRY—DISTRIBUTION

For the lighting of the interiors of buildings, except in the case of certain large halls and such like structures, arc lamps are unsuitable. For ordinary rooms the light would be too powerful, and for rooms where the total amount of light required is sufficiently large to equal that of an arc lamp, there would generally be an objection to the concentration of the whole of the light at a single point.

Fortunately there is a second class of lamp which is capable of meeting every such requirement. It is the well-known incandescent lamp, and consists of a very thin strip or filament of the purest obtainable carbon wholly enclosed in a glass bulb from which the air has been carefully exhausted; the connection between the carbon and the external conducting wires being secured by short pieces of platinum wire fused through the glass. The passage of a sufficiently strong current through the filament causes it to be raised to a white heat, when it is, of course, intensely luminous. It may perhaps be advisable to discuss briefly the principles upon which such a lamp must be constructed before describing more fully the actual processes.

It was shown when discussing the Cardew Voltmeter, that if a current of electricity is urged through a solid conductor, heat is developed, and that the amount of heat so developed is proportional to the total energy expended in the conductor. It was also shown that this energy is proportional to the product of two factors, viz., the strength of the current C, and the difference of potential E between the extremities of the conductor, necessary to maintain that strength—or the heat H developed is proportional to E C; but by Ohm's Law $E = C R$, therefore $E C = C^2 R$.

It is manifest from these simple formulæ that the heat developed varies directly as the resistance, and directly as the square of the current strength. If we have two equal and uniform conductors A and B, and maintain a potential difference at the ends of one of them, A, twice that at the ends of the other, B, the heating effect will be quadrupled; for with equal resistances the current strength will also be doubled, and in fact energy is being expended four times as fast in A as compared with the rate of expenditure in B. If, however, while both conductors are of the same length and sectional area, the specific resistance of B is twice that of A, and the same potential difference is maintained in both of them, the resistance of B being twice that of A, will halve the strength of the current flowing through B. Hence if in A, $H = EC$, or C^2R, then in B, $H = \frac{1}{2}CE$ or $2R\left(\frac{C}{2}\right)^2 = \frac{1}{2}C^2R$. In this case twice as much heat is developed and twice as much energy is expended in A as compared with B. Again, if the current in B is made equal to that in A, by doubling the potential difference in the former, then in A, $H = E\,C$ or C^2R, and in B, $H = 2EC$ or $2C^2R$, so that doubling the resistance and keeping the current strength constant, doubles the heat developed and causes twice the amount of energy to be expended. One great lesson is here again enforced, viz., that the amount of energy obtained in the form of heat can only equal and never by any possible means exceed the amount of electrical energy expended or absorbed in the conversion.

The relation between heat and temperature has already been discussed, but we must again refer to it here, as it is of the utmost importance. Let us suppose that instead of employing a conductor of increased specific resistance, we experiment with two samples of the same material and of the same sectional area, but that one of them, B, is twice as long as A; then the resistance of B will also be twice that of A, and if equal currents are urged through these conductors, the heat developed in A will be only half that developed in B; but as B is twice the length of A, and has therefore twice as much matter in it, the temperature of the two conductors will be equal. Now when a body is made very hot it becomes luminous, and the luminosity of a body is proportional to its temperature. In this experiment, therefore, the temperature of A and

B being equal, the luminosity will be equal, although B absorbs twice as much energy as A, because its resistance is double. Now if the resistance of B is made double that of A by halving its sectional area instead of by doubling its length, and equal currents be urged through each as before, we still get twice as much energy absorbed, and therefore twice as much heat developed in B as in A. And since the mass, or the quantity of matter, in B is now only half that in A, equal quantities of heat would cause the temperature of B to be twice that of A; therefore, as twice the amount of heat is developed in B, its temperature is raised to four times that of A. This clearly indicates the direction in which we should work in order to raise a conductor to a very high temperature. Stated generally, a large amount of energy must be expended on a small mass of matter; therefore the conductor must have a high resistance, and in order to keep its mass small this high resistance must be obtained by diminishing its sectional area rather than by increasing its length, and further, the material chosen should be one which has a high specific resistance.

Men were not long in conceiving the idea of employing the heating effect of a current upon a conductor for illuminating purposes, and patents based upon this principle were taken out nearly fifty years ago. But these early efforts were one and all of them failures from a commercial point of view, although some of them were identical with many of those of a comparatively recent date. It was seen that a conductor of high specific resistance was necessary, and this limited the number of materials available. This number was further reduced by the fact that most conductors either melt or volatilise at comparatively low temperatures—before, in fact, the temperature of white heat is attained. Iron, which is cheap and has a high resistance, and which might therefore be considered a suitable substance, unfortunately melts at a comparatively low temperature. It is for this reason useless as an illuminant. It also oxidises or combines with the oxygen of the air as its temperature rises. German silver is for similar reasons not available. We are, indeed, limited among the metals to the expensive platinum or its alloys, unless we take into account the experiments which have been made with iridium, an even more expensive and very scarce metal, and one which, if equal to the

requirements, could probably not be procured in sufficient abundance to meet the demand. Platinum is capable of being raised to a bright white heat, and can then emit light of dazzling brilliance. It has also the advantage of being practically inoxidisable. The critical temperature is, however, suddenly reached ; that is to say, above a certain point, a slight increase of temperature suffices to produce liquefaction, and therefore to cause a rupture and so disconnect the circuit. It must also be remembered that the resistance of metals increases materially with an exaltation of temperature, a fact which hastens the fracture of the wire. Efforts have been made to prevent this overheating by means of automatic regulators, which short-circuit the lamp when the current reaches a certain predetermined strength, and so cut off the current just at the moment that there is a risk of breaking the wire. Some of these are clever laboratory expedients, but nothing more. If, then, we had been restricted to metallic conductors, electric lighting by incandescence would long since have been given up as impracticable. Carbon, however, which is a non-metallic body, is a fairly good conductor of electricity, although of considerably higher specific resistance than platinum. A very remarkable feature pertaining to it is that its resistance decreases with an increase of temperature. It is a substance which cannot by any ordinary means be melted or volatilised (although a temperature has been attained at which it becomes flexible), so that in this respect it is superior to platinum or any other of the metals. It, however, oxidises readily when heated in an atmosphere containing free oxygen, such as ordinary air. This difficulty was for a long time insurmountable, although many efforts were made to overcome it, such as placing the carbon under a glass receiver, and depriving the enclosed air of its oxygen by means of a piece of phosphorus, a substance which oxidises readily at ordinary temperatures. In this case, the carbon is suspended in an atmosphere of the remarkably neutral or inactive gas nitrogen. But even such an arrangement as this was soon found to be clumsy, unsatisfactory, and in fact impracticable. Even supposing it to have been otherwise, the carbon procurable was very defective. Thin rods of graphite or gas-retort carbon such as is used in the Bunsen cell, or sections of the artificially prepared material such as is used in the Leclanché cell, were

tried; they could not, however, be obtained of sufficiently small sectional area, and were too irregular in structure to prove practicably useful. Efforts were also made, and with a better prospect of success, to accomplish the object in view by placing the carbon in the then best obtainable vacuum. The vacua were for a very long time far from perfect, and as a consequence the durability of the carbons was very brief; but when it was shown how it was possible to secure an all but perfect vacuum, a fresh impetus was given to the idea of lighting by the incandescence of thin pencils or, as they were subsequently called, filaments of carbon. Since then, the real improvements that have been made have been in the formation and fixing of these filaments, which can now be prepared from almost any substance having a large proportion of carbon in its composition. As organic substances consist to a great extent of carbon, and as these substances can generally be decomposed somewhat readily, it is only natural that they should form the basis from which the filaments are manufactured. Filaments as they are now made, can be divided into two classes, (1) those in which the fibrous structure of the carbonaceous body is retained, and (2) those in which the original or organic structure is altogether destroyed during the process of manufacture, and the material rendered thoroughly homogeneous. To the first class belongs the Edison lamp, and to the second class the lamps of Swan and the majority of other inventors. It is a remarkable fact that Edison asserted in his patent that to give the carbon the highest possible resistance and the smallest tendency to disintegration it should retain its structural character, and that such carbons alone possess these qualities, qualities which are impaired by any treatment tending to fill up the cells or pores with unstructural carbon, or to increase the density or alter the resistance of the fibre. Swan, on the other hand, maintained that the structure of the material should be entirely destroyed, and the carbon filament made as dense as possible. Although good and efficient lamps can be manufactured on either of these principles, experience seems to show that the latter or homogeneous filament is the better of the two.

It might have been gathered from what has already been said that the chief desiderata in a good lamp are: (1) that the filament shall be sealed in an air-tight vacuous glass vessel; (2) that efficient

means shall be provided for connecting the filament with the external circuit ; (3) that the filament shall offer considerable resistance ; (4) that it shall have a small mass, so that its temperature shall be raised as much as possible by a given quantity of heat ; (5) that it shall be durable at high temperatures in a vacuum ; and (6) that the lamp shall be capable of being manufactured at a small cost, and of any desired dimensions or resistance. It is the last of these requirements which gives the greatest trouble in meeting, because a slight variation either in the thickness or sectional area, or in the amount of radiating surface of the filament, causes a considerable difference in the luminosity.

The filament in the Swan type of lamp is made either direct from cotton thread, or from a thread formed by squirting a solution of cellulose through a fine nozzle at high pressure, cellulose being the chief constituent of such vegetable substances as cotton, linen, paper, &c. The first process with the cotton is that of parchmentising it. This is no secret, the method adopted being the same as that for making ordinary parchment paper. A solution of two parts of sulphuric acid to one part of water having been prepared, the cotton thread (which should be of a loose texture, such as knitting or crochet cotton) is wound on a drum, from which it is passed slowly through the acid solution. During the passage the acid acts on the fibres and gradually destroys their molecular structure, partially dissolving the material, and converting it into a gelatinous semi-transparent state, as cellulose, having a chemical composition of $C_6H_{10}O_5$. Having been brought to this condition, it is passed over freely revolving rollers or pulleys into a bath of running water, where it is slowly and uniformly wound on to a large perforated metallic drum. When the drum is covered it is removed and placed in another water bath, to ensure a thorough washing. It is absolutely essential that every particle of acid should be removed, for were any left behind, it would on drying destroy the thread by dissolving it. After being thus thoroughly washed, the drum is removed from the water and placed aside, to allow the thread to dry. When first placed in the washing bath it gradually loses its transparency, becoming white and opaque. But on drying, it returns to the transparent state, with the additional property of being remarkably tough,

becoming a horny thread, with every trace of the original twist destroyed.

This process can be carried out in a small way, and is very instructive. A piece of knitting cotton is wound round a piece of glass, or better still, round a frame made of pieces of glass rod. It is then dipped into the acid solution of the proportions above mentioned. The process must be carefully watched, and if the action has been of just sufficient duration, but not lasting too long, the change from the fibrous to the homogeneous state will be readily seen. It should then be placed in water, well washed and dried. The drying is best performed by stretching the thread gently in a straight line, or if too lengthy, over a series of pulleys. If the thread is left in the acid too long, the solution is carried too far and the thread weakened, so much so as not to be able to bear its own weight even in a length of a few inches. The same thing happens if the thread on being removed from the acid is placed on a plate or piece of glass, instead of being at once immersed in the water; the acid remaining in the thread completes the dissolving process, and liquefaction ensues. It is possible to remove the thread from the acid too soon, the defect then being that the destruction of its fibrous character is only partly performed.

The thread having dried, it is next reduced to a uniform gauge throughout, which is done by drawing it through a series of jewel dies decreasing slowly in diameter. It is then subjected to the process of 'carbonising,' or converting it into a solid carbon filament. The thread is first wound on a frame consisting of two round carbon or porcelain rods kept in position by being fixed into holes in two side-pieces. The round rods are sufficiently far apart to make each bend of the thread correspond to one filament, for it is in the process of carbonising that the filament is definitely shaped. In order to make the loop which was at one time one of the characteristic features of the Swan filament, the thread is turned twice round one of the carbon rods in the frame before passing to the other rod. One object of this formation is to get a long filament in a comparatively small bulb. The frame having been filled, pieces of cardboard are placed on its sides or faces to prevent accidental injury to the threads, the whole being then wrapped

round with paper. A number of such parcels is placed in a crucible or cast-iron box, until the vessel is nearly full. Powdered charcoal having been shaken over the contents to fill up any spaces that may have been left, the lid is placed in position, and an air-tight joint made with a little fireclay. As the powdered charcoal gets hot it absorbs any free oxygen that may be in the crucible and prevents any getting to the filaments; were it to do so, it would speedily destroy them. The crucible being thus prepared, is placed in a suitable furnace and raised slowly to a white heat. The gradual increase of temperature is important in determining the shapeliness of the filament. Too rapid an increase in temperature might alter the dimensions of the frame and cause the threads to sag, so that the form of the filaments would be more or less distorted. The high temperature is necessary to render the carbon hard and durable, to increase its conductivity, and to reduce its capacity for holding atmospheric and other gases within its pores. This last-mentioned feature is not only interesting, but it is also fraught with the utmost importance. All substances are more or less porous, and have the power in varying degrees of holding gaseous particles within those pores, a power or property known as occlusion. As the temperature of a body rises these gaseous particles expand and force themselves through the substance, frequently causing minute fissures; with some substances which do not liquefy, such as carbon in its ordinary form, this power of occluding gases returns with a resumption of the normal temperature. It is, therefore, imperative that the nature of the carbon should be so altered as to prevent this taking place. Hence the necessity for thorough carbonisation at a high temperature.

This alteration in character of the carbon is continued in the next process, which is that of 'flashing.' Before proceeding with this process, however, the filaments are cut to about the desired length, sufficient margin being allowed for making connection with the platinum wires, which pass through the bulb to the external circuit. The filament is then held by a pair of clips, connected with suitable terminals, by means of which a dynamo, or, better still, a battery of secondary cells, can be joined on. The suspended filament is then placed in an atmosphere of some hydro-carbon, more generally ordinary coal-gas (which is rich in

carbon) and traversed by brief currents sufficiently strong to raise it, or portions of it, to a white heat. The effect of this process is to partially decompose the gas which is at the ordinary atmospheric pressure, and to cause a deposition of carbon particles on the surface of the filament. Should there be, as is generally the case, any inequality in the filament, causing a variation in its resistance, one portion will be raised to a higher temperature than another, and upon this hotter section a greater deposit of carbon will take place. The flashing process is therefore continued until the carbon assumes a uniform temperature—that is to say, until it becomes uniformly luminous throughout. The process also serves to reduce the power of occluding gases in the interstices between the particles. The filament is next placed in an exhausted receiver, and a continuous current passed through it, the result being that the carbon is hardened, the conductivity increased, and the power of occlusion eventually destroyed; but to bring about these results the temperature must be raised to a white heat, the current being maintained until the resistance is reduced almost to the required limit. The final flashing may, however, be reserved until the filament is fixed in the bulb and ready for finishing off.

Platinum wires are always employed in mounting the filaments, as platinum is the only metal which has a coefficient of expansion nearly equal to that of glass: that is to say, it expands or contracts with variations of temperature at almost exactly the same rate as glass, so that it can be fused into that material without any risk of its subsequently fracturing the glass on cooling. The wires are first fused along the sides of a short piece of glass rod, or have a little molten glass twisted round them while they are held in position. In the former case, a piece of glass tubing is fused over the rod, thereby encasing the wires for a portion of their length. The coefficient of expansion for white glass is 0·0000086, while for platinum it is 0·0000088, so that these two substances agree very closely in this respect. The coefficient for wrought-iron is 0·0000122, or about 50 per cent. higher than that for glass, while for other metals the disparity is still greater. Efforts have been made in America to use long pieces of iron wire embedded in a zigzag fashion in the glass, and to rely upon the minute irregularities in the relative disposition of the glass and iron to keep them

together and to prevent small quantities of air from entering the bulb and so destroying the vacuum. Experiments have also been made with a number of alloys. Mr. Fessenden, of New Jersey, claims to have succeeded with an alloy of silicon with such substances as iron, nickel, and gold. The anxiety to find a substitute for platinum arises from its scarcity and consequent high price. This is the only objection, for in all other respects it answers admirably. The supply is derived almost entirely from Russia, where important mines are being rapidly developed and new sources opened up. After all, however, the cost of the platinum is only about 5 per cent. of the cost of the lamp.

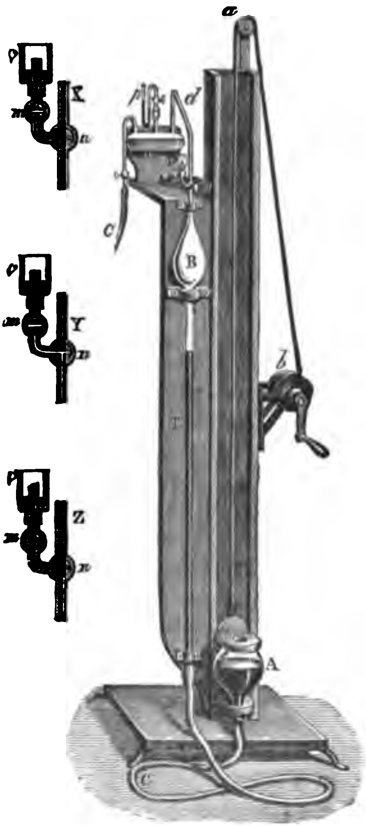
The connection between the carbon and the platinum is made by flattening out the ends of the wires into minute plates, which are then bent gently round the ends of the filament, to which they are fixed with carbonaceous cement. The joint is completed by carbonising the cement by means of a strong current sent through it. Instead of using the cement, the joints are sometimes perfected by immersion in a hydro-carbon liquid or gas, the filament being short-circuited and the joints raised to incandescence by a strong current, causing a decomposition of the hydro-carbon, and a deposition of the carbon upon the joints. There are several other methods of mounting, but they are mostly based upon or are modifications of those above described.

The next process is that of exhausting the bulb of its contained air and moisture. This has to be performed carefully, and it is here that some of the greatest difficulties are met with.

The vacuum obtainable in an ordinary mechanical air-pump is, as we have already indicated, far from perfect, and useless for the purpose. There are, however, two types of mercurial air-pumps which are so far superior to the mechanical form that they can produce even higher vacua than are actually required for lamp-making. It is, of course, well known that if a long glass tube, say 36 inches long, sealed at one end, is filled with mercury and then inverted with its open end under the surface of mercury contained in a basin or other convenient vessel, the liquid metal in the tube will sink until its surface is about 30 inches above that of the mercury in the basin—until, in fact, just a sufficient height of mercury is left in the tube to balance the atmospheric

pressure on the mercury outside. It follows that the space in the tube above the level of the metal is a more or less perfect vacuum, and it is generally known as a Torricellian vacuum, owing to the fact that Torricelli was the first to perform the experiment.

Fig. 300.



The Geissler pump, although but a modification of the Torricellian apparatus, is an instrument of considerable value. A laboratory form of this pump is illustrated in fig. 300. A is a glass vessel or reservoir which is connected by a piece of flexible tubing, C, with a barometer tube, T, terminating, at its upper extremity, in a glass reservoir, B, which may be called the pumphead. This latter reservoir is connected to a three-way tap, *n*, of which enlarged views are given at X Y Z. When this tap is turned, as at Z, communication between B and the outer air at *v* is established, an additional ordinary tap being, however, interposed at *m*. When *m* is turned off, as at Y, communication with the outer air is shut off; but if *n* is turned into the position shown at X, the pumphead is connected to the tube *d*, which leads into the drying tube *o*, containing sulphuric acid. The receiver or other vessel to be exhausted is connected to the tube *c*, which also leads into the drying tube. A small manometer or pressure gauge, *p*, also communicates with *o*, and serves to indicate the degree of exhaustion obtained. The reservoir, A, has a cord

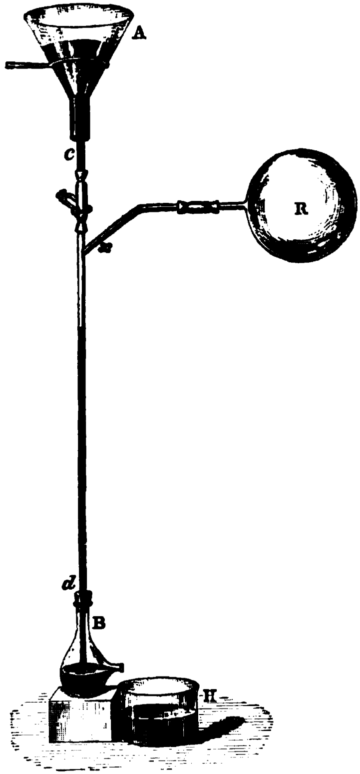
attached to it, which, passing over the pulley, *a*, is fixed to the drum, *b*. By means of the handle attached to this drum, the reservoir can be raised or lowered through a distance of nearly 4 feet.

If now A is placed at the top of its range, the taps *n* and *m* being open as at Z, the mercury on being poured in will fall down the tube C and rise in T until the pump-head, B, is full, or until the mercury columns in the two tubes are balanced. The air in T and B will, of course, be expelled at *v* as the mercury rises in the tube. Supposing the taps to be next turned so as to shut off communication with the outer air and connect B with the receiver or incandescent lamp bulb which is to be exhausted, and then the reservoir, A, to be lowered sufficiently, the mercury will flow out of B and down T until it is just balanced by the pressure of the air on the surface of the mercury in A. The air in the receiver or bulb then expands uniformly so as to occupy the space in the pump-head and tube above the mercury. The tap *n* is again turned so as to shut off the receiver. On raising the reservoir, A, the mercury again rises into B, and the taps being turned so as to open communication with the atmosphere, the contained air is driven out. This done, *n* is once more turned so as to open communication between the receiver and B, and cause the air left in the receiver to again expand when A is lowered. This air is in its turn expelled, and the process repeated. The operation is obviously a very slow one, although it is possible with this apparatus to obtain very high vacua.

The other type of mercurial pump to which we have referred is the Sprengel, the fundamental principle of which is illustrated in fig. 301. It consists of a stout glass tube, *c d*, 39 or 40 inches long, with a branch *x* connected to the vessel R to be exhausted. A large funnel-shaped reservoir, A, supported by a stand, is connected to *c d* by means of a piece of india-rubber tubing, the size of the channel through it being adjusted by means of a pinch-cock. The lower end of *c d* dips below the surface of the mercury in the flask B, which is furnished with a spout a little higher than the bottom of *c d*, in order to allow the mercury to pass out into the reservoir, H. The pinch-cock is so adjusted as only to allow the mercury to pass down the shaft a drop at a time. Each drop

constitutes a plug or piston which fits closely to the sides of the glass, and in its descent drives before it any air that may happen to separate it from the drop beneath it. The shaft *c d* is to all intents and purposes a barometer, so that the drops of mercury accumulate until a column is formed about 30 inches high, the actual height depending upon the counter-pressure of the outer air at the time being. Hence the distance which the mercury pistons ultimately fall is only 9 or 10 inches. It will be evident that as the drops fall, and tend to establish a vacuum above them, the air in R expands and part of it occupies this otherwise vacuous space. Consequently as each piston passes the junction of *x*, the air is swept out little by little until finally a very good vacuum is obtained in R. When the degree of rarefaction becomes considerable, the pistons fall smartly upon the column of mercury and give out a distinct metallic ringing sound. This hammering frequently sets up such strong vibrations as to fracture the glass; and it is this which really limits the length of the shaft. As the mercury falls on the barometric column, an equal quantity is, of course, driven out at the lower end, carrying with it, also, the bubbles of air which separate the little plugs. The mercury collected in H is replaced in A as necessity arises. This process is also very long and tedious.

FIG. 301.



The exhaustion can be materially hastened by employing a

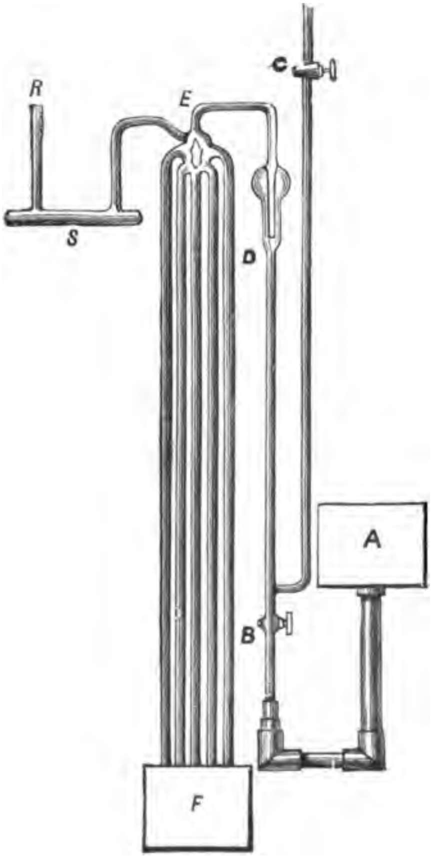
good mechanical air-pump to exhaust the system as far as possible by mechanical means, the process being afterwards completed with the mercury pump. A simple barometer gauge can also be used to indicate, by the height of its contained mercury, the degree of exhaustion obtained.

These are the two systems of pumps upon which the apparatus actually employed in exhausting incandescent lamp bulbs is based. These simple forms are, however, open to many serious objections. A film of air always attaches itself to the surface of glass, and at times some difficulty is encountered in getting rid of it. Air is also supposed to be confined in the mercury itself, but there is some doubt on this point. To get rid of other impurities the mercury should always be distilled, and never allowed to get dirty by contact with brass or any other substance which it is likely to attack. Ordinary air always contains more or less moisture, and to remove this, the air as it is exhausted from the lamp bulb is made to pass through sulphuric acid or phosphoric anhydride in order to dry it before it is allowed to enter the pump. Grease used for lubricating taps is also injurious for similar reasons, and should, therefore, be avoided. Taps themselves are serious offenders. No matter how perfectly they are made, they must allow some air to enter the pump, more especially when high vacua are obtained, and when, therefore, the prespure of the outer air on the tap is very considerable. To overcome this difficulty, taps are now superseded in the essential portions of the pump by small glass valves moving up and down in the pump as the mercury rises and falls. Their ends are ground to fit the seating, the passage being effectually sealed by a small ring of mercury which is retained as the valve drops into position. One of these valves is shown at D, in fig. 304.

But mercury, like other bodies, is more or less volatile, and when the exhaustion in the pump is carried beyond a certain point the exceedingly small pressure on the mercury surface permits vaporisation to take place. Although the degree of exhaustion of incandescent lamp bulbs is comparatively low, and not sufficient to cause any considerable amount of vaporisation, it may be interesting to mention a device by Mr. Crookes for keeping the vapour out of the receiver to be exhausted. Between

the receiver and the pump he placed a long tube containing in the middle of it a little iodine, on each side of which was placed powdered sulphur. The mercury vapour was arrested by the iodine and converted into solid iodide of mercury. The iodine, which is itself volatile, was prevented by the sulphur from getting out of the tube either way, by its conversion into iodide of sulphur. But there was also a risk of the sulphur getting out of the tube, and this was prevented by placing in its path powdered silver, which, combining with sulphur vapour, would form sulphide of silver. In this way it would be possible to prevent any mercury passing into the receiver, which would, therefore, contain nothing but the exceedingly minute residuum of air.

FIG. 302.



One of the most practical forms of pump is that of Mr. Gimingham, the factory type of which is illustrated in fig. 302. A large vessel, A, is employed to supply several pumps, the flow of mercury through each pump being regulated by the tap, B. The mercury is driven up the tube D and enters the pump-head at E, where the drops are divided between five Sprengel fall-tubes, carrying with them the air from the lamp bulb attached to R,

which on its way to the pump passes through the horizontal drying tube S. The mercury plugs fall into the reservoir F, whence the metal is lifted by a force-pump into A again. But as the mercury is very liable to carry with it minute air-bubbles, which would be given up in the pump and impair the vacuum, some device becomes necessary for arresting these atmospheric particles. The bubbles usually find their way to the surface of the glass, and slide upwards with the mercury. This fact permits the adoption of a very simple but effectual form of 'air-trap,' as shown near the top of the tube D. The tube is at this point enlarged to a bulb, through the top of which is fused the tube leading to E. This inner tube is open at its lower end, which is clear of the outer tube, so that the mercury on rising passes freely through it on its way to the pump, while the air-bubbles continue their course along the surface of the glass, and are consequently arrested or trapped in the upper part of the bulb.

A more elaborate form of the same pump is shown in fig. 303, for which we are indebted to the Council of the Society of Arts.

The supply vessel A communicates by a long flexible tube with a forked tube *c*. The tube on the left, which is controlled by the pinch-cock *r*, leads through two air-traps, *n*, *m*, to a McLeod pressure gauge, an appliance used for measuring the pressure in very high vacua where the ordinary means of measurement are not available. The process consists in compressing a large but known volume of the rarefied air into a comparatively small space also of known dimensions, and then measuring the pressure under the altered conditions. The tube on the right, controlled by the pinch-cock *q*, leads through the air-traps *h*, *i* to the pump-head, where the mercury divides between the five fall-tubes, which are about 39 inches long, and which discharge into the capacious reservoir shown at the bottom. The tube *t* is the exhaust tube, having three branches, one, *s*, leading to the McLeod gauge, another, *l*, to the barometric gauge, *u*, and another through the drying and absorbing tubes, *x* and *y*, to the lamp bulb. A comparison barometer is placed at *w*. The supply vessel A is lowered from time to time, and communication established with the collecting vessel, so as to allow the mercury after it has passed through the pump to refill it. In experimenting it is sometimes necessary

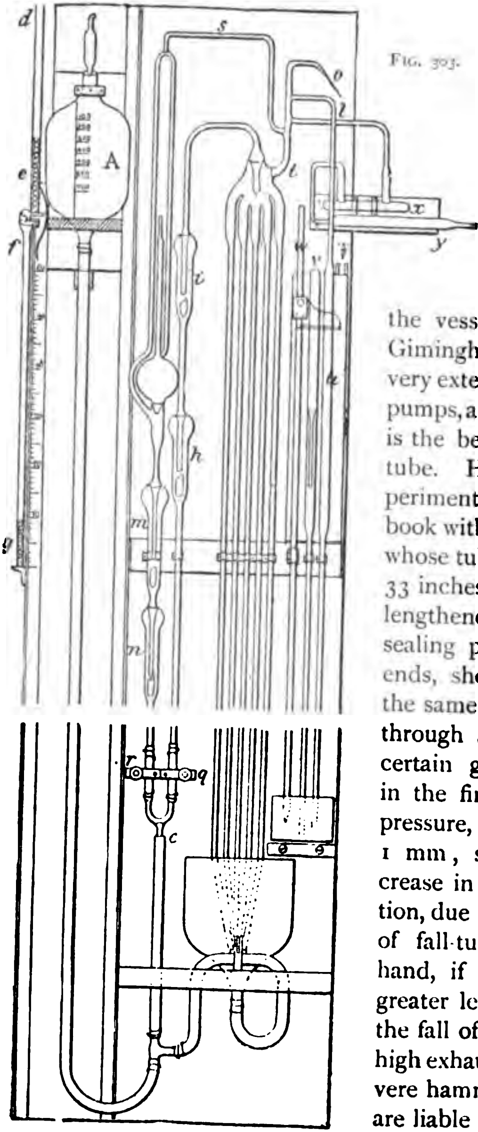
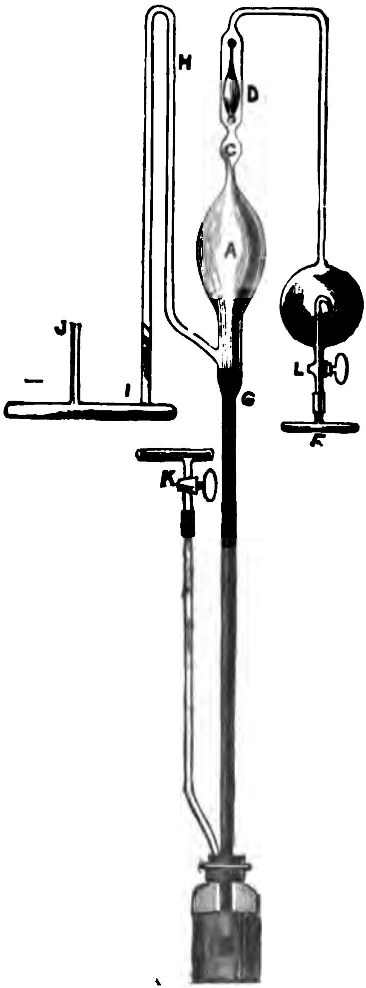


Fig. 303.

to count the number of times this vessel is raised; this is done automatically by the tubes *d e* and *f g* with the aid of a few leaden shot, one shot being made to fall from the upper to the lower tube every time the vessel A is raised. Mr. Gimingham has experimented very extensively with mercurial pumps, and finds that 39 inches is the best length for the fall-tube. He says that 'An experiment recorded in my note-book with a five-fall tube pump whose tubes were at first made 33 inches long, and then were lengthened to 39 inches by sealing pieces to their lower ends, shows that by passing the same quantity of mercury through at the same rate, a certain globe was exhausted in the first case to 50 mm. pressure, and in the second to 1 mm., showing a great increase in the rate of exhaustion, due to the extra 6 inches of fall-tube. On the other hand, if they be made of a greater length than 39 inches, the fall of the mercury at the high exhaustion causes such severe hammering that the tubes are liable to be fractured.'

From other experiments he deduced that in the higher stages of the exhaustion, the air particles, instead of being swept out by the pistons, are taken out by a process of entanglement with the mercury.

FIG. 304.



Mr. Swinburne has devised a simple and useful pump (fig. 304). It consists of a bulb, A, on a long shaft, G, which passes through an air-tight stopper nearly to the bottom of the bottle B. The bulb is drawn to a point at the top, and the tube is enlarged into a little bulb at C. It is again contracted where it joins the valve tube D. From the top of D there is a tube to the globe E communicating with the tube F, which serves for a number of pumps and in which a vacuum is maintained by a mechanical pump. H leads to the drying tube I, and J to the branch tube on which the lamps are sealed. The pump is started by opening the tap L, but the bent tube leading into the globe E is drawn very fine, so that the exhaustion takes place gradually. The bend in this tube prevents any globules of mercury that may be drawn over into E from getting into the vacuum tube F. When the vacuum in the pump and lamps has been brought to about half an inch, communication with F is cut off by turning the tap L, and

the tap K is opened, and a higher vacuum developed by subjecting the mercury in B to alternations of ordinary atmospheric and high-air pressure. The height of the mercury shown in the shaft G is that due to the ordinary atmospheric pressure in B, so that when the high-pressure air descends through K, the mercury is driven past the opening of the tube H, through the bulb or pump-head A, through C, and half way up the tube D. The extra pressure being now removed from B, the mercury descends, the valve in D closing the opening into C before it has all fallen, so that the valve is sealed by the mercury. The mercury continues to fall till it reaches the level G, whence a further exhaustion by expansion from the lamp bulb takes place. This small quantity of air is in its turn expelled, and the Geissler action continued until the necessary degree of exhaustion has been obtained. The little bulb C is introduced to prevent the mercury rising and hitting the valve smartly when the exhaustion approaches completion. Were it allowed to do so the air would probably be driven against the side of the glass and stick there. It will be evident that, as the passages both above and below D are exhausted, a very small pressure will suffice to raise the valve.

Reverting to fig. 301, it will be apparent that if the atmospheric pressure in B is reduced, the mercury column in the shaft *c d* will be shortened, whence a shorter shaft will suffice. In pumps of this pattern devised by Mr. Stearn there are three fall-tubes, each 10 inches long, completely enclosed in a partially exhausted chamber.

Such pumps are finding considerable favour, but they introduce a further risk, for if anything happens to interfere with the partial vacuum, the mercury will be driven up with considerable force and get into the upper parts of the pump, possibly breaking it.

Many suggestions have been made to heat portions of the mercury pump with a view to hastening its action, and pumps have been constructed to suit this purpose, but they do not seem to have met with much success in practice. Vacua can now be obtained far in advance of the actual requirements, the most perfect vacua being developed by the absorption of the residual gas after the exhaustion has been pushed as far as possible by the

mercury pump. This is done either mechanically or by using some substance with which the air particles combine chemically. Professor Dewar has produced a vacuum which he estimates at $\frac{1}{350}$ of a millimetre by heating charcoal to redness in the vessel exhausted by the Sprengel pump.

Mr. W. Crookes says he has obtained a vacuum of one-hundredth of a millionth of an atmosphere, which is equivalent to one-tenth of an inch at the top of a barometer tube 200 miles in height. That would appear to be an almost perfect vacuum; but such is the smallness of the molecules of matter, that were a small tube containing a centimetre of air exhausted to that extent, there would still be left in it ten billion molecules.

Although it is, evidently, a comparatively simple matter to obtain the degree of exhaustion necessary for incandescent lamps, there are several causes for a deterioration manifesting itself in the vacuum after the finished lamp has been laid aside for a time, such as the occlusion of gases by the carbon and platinum, and by the cement employed to connect them together, and the very thin film of air which is liable to adhere to the inner surface of the bulb. In order to expel these gases, the filament is raised to incandescence during the later stages in the process of exhaustion, or the heat is applied externally.

The lamp having been sufficiently exhausted, the small glass tube connecting the bulb to the exhaust tube is fused, drawn out to a thread, and the lamp sealed off.

The vacuum is usually tested by means of an induction coil; one method is to fuse two platinum wires into a glass tube leading to the lamp, and simultaneously exhausted with it, and to connect these wires to the terminals of the secondary coil. The distance between the ends of the platinum wires inside the tube is so adjusted that when the required degree of exhaustion is attained the spark passes through the air outside the tube in preference to traversing the vacuous space between the platinum points. Another method applicable to the finished lamp is to connect one end of the secondary to the filament, and the other to a loop wound outside the bulb, the quality of the vacuum being determined by the relative feebleness of the discharge which takes place between the filament and the bulb. When the lamp is

badly or imperfectly exhausted the filament 'burns'—that is to say, it oxidises—but it also requires a greater amount of heat to raise and maintain its temperature at the required point, owing to the fact that the air particles carry a portion of the heat away by convection.

The filament of the Edison lamp—which, although now obsolete in England is still employed in America—is made from bamboo, which is carefully cut into very fine strips of the required length, provided with little enlargements at the extremities to facilitate the fixing to the platinum wires which are fused through the bulb.

The carbonising and subsequent processes are similar in principle to those already described, the method of fixing the carbon to the platinum being, however, somewhat different. The flat ends of the carbon are mechanically gripped by the platinum, and the junction is made electrically perfect by a small coating of copper deposited electrolytically—that is to say, the joint is connected to the negative pole of a battery, and is then placed in a bath or vessel containing a solution of copper sulphate, in which is immersed a copper plate connected to the positive pole of the battery. As the current passes through the solution, copper particles are dissolved off the copper plate, and an equal number of particles precipitated upon the joint. Electrical continuity is in this way ensured, but during the subsequent working of the lamp there is a tendency towards the disintegration of the copper, which is sometimes deposited upon the inner surface of the bulb as a thin metallic film.

Such are the general features pertaining to the construction of the Swan and Edison lamps, but the many competing manufacturers who have availed themselves of the lapsing of the patent rights adopt methods of a very similar character, and we need only refer in the succeeding pages to one or two of them.

For ordinary purposes the filaments are shaped either as single or double loops. There are, however, several ways in which connection is made between the lamp and the external circuit, involving a corresponding variety in the form of the lamp-holders.

Figs. 305 to 309 illustrate the methods more generally em-

ployed for connecting the filament to the external circuit. In one of the lamps, fig. 305, the outer ends of the platinum leading wires are simply bent into small loops, the class of holder used being provided with two spiral springs connected to the circuit leads. The free ends of the springs are passed through the lamp loops, the shoulder of the lamp fitting into the outer heavy spiral,

FIG. 305.

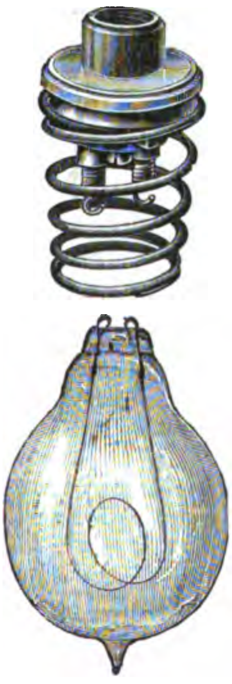


FIG. 306.

which is just sufficiently long and rigid to keep the smaller spirals extended, and so to make good electrical connection. This type of holder should, on account of the small area of contact, only be used in places subject to considerable vibration, and where with other types there would be a risk of the lamp being shaken out of contact.

The top of the lamp shown in fig. 306 is provided with an insulated brass collar fixed with cement, the filament being connected to the two brass segments embedded in the cement. The collar has two small pins, which fit into the 'bayonet-joint' holder shown in the figure. There are many varieties of this type of holder, but a sectional view of one of the best—that made by the Edison and Swan Company—is given in fig. 307. A perspective view of the electrical portion of the holder is also given in fig. 308. This part is mounted on a circular porcelain base held in the position shown in fig. 307 by a series of brass collars. Two holes (only one is shown in the section) are made in the base, and through each hole a connecting wire is passed, and clamped into a small brass contact block by means of a set screw. This block is an extension of a small socket, which carries a brass spiral spring, the lower end of which presses against a brass plunger and strives to keep it out as far as it will go, a small flange on its base preventing it from being wholly ejected. The two plungers, with their sockets, &c., are clearly shown in fig. 308.

FIG. 307.

In twisting the lamp into the holder the segments make rubbing contact with the two plungers, and the lamp is thus thrown into circuit by the mere act of fixing it in the holder; but as the free ends of the plungers are rounded, the contact between them and the brass segments in the lamp is small and very much circumscribed in area, it may almost be called a point-contact. This is a certain source of heat and consequent loss of energy, and the limited areas of the various contact surfaces in this form of holder render it altogether unsuitable for high candle-power lamps—that is to say, for lamps taking a heavy current. It is, nevertheless, the favourite type for general work, and it is usually of much better manufacture and mechanical finish than its more frequent competitor, the Edison

FIG. 308.

'screw' holder, which is illustrated in fig. 309. In this case one end of the lamp filament is connected to the coarse screw thread stamped out of thin sheet brass and set in plaster, and the other end to the insulated brass stud projecting from the bottom of the lamp. This affords another means of throwing the lamp in circuit by the act of placing it in its holder, which is provided with a corresponding brass screw thread and a small brass disc mounted on a stiff insulated spring, which maintains contact with the stud on the lamp. The screw-thread and stud in the holder are electrically connected with a pair of set-screws fitted in the body of the holder, and to which the external wires are attached. With good workmanship and substantial metal fittings, instead of the flimsy stampings usually employed, this should be a most efficient holder. It is often noticed that although the lamp when first screwed into the cold holder fits tightly, it is found to be very loose after the current has been passed through the lamp for some little time, and that it is then possible to give the lamp another half turn or even more. This is probably due to the relatively greater expansion of the holder than of the lamp collar. On cooling the lamp does not again recede, but is simply held more firmly in the holder, so that there is no need to fear from this cause a recurrence of the bad contact. There is another source of trouble with this type of holder. In fig. 310 is illustrated (full size) the porcelain ring which serves the double purpose of insulating the brass screw thread from the rest of the holder and of helping to keep the lamp in position. This porcelain ring frequently breaks, more especially under bad usage, and short circuits have often been established in consequence.

FIG. 309.

Lamp-holders are sometimes provided with small switches

for making and breaking the lamp circuit, the switch action being generally controlled by a tap-handle similar to those used for gas-burners. In the Edison holder or socket (fig. 309), the tap carries a cam, which works against the small brass plate, which is pressed against the stud on the bottom of the lamp. It releases with a snap action. Socket switches are, however, very unsatisfactory, and easily get out of order. The great defect is in their mechanical design, and the difficulties in the way are considerable. This will perhaps be evident when the smallness of the parts and the comparatively high temperature to which the holder is raised are taken into consideration. Switches are, however, more generally independent, and fixed in convenient positions on the walls, &c., and one or two forms of them will be described in the following chapter.

FIG. 310.

Incandescent lamps can be made to yield any required degree of illumination, from a fraction of a candle-power up to as much as 1,000 or even 2,000 candle-power, and as the bulb and filament can be made in almost any shape, it is only natural that there should be a great variety of types designed for correspondingly varied purposes. For ordinary lighting purposes lamps of 8, 16, or 32 candle-power are the sizes most generally adopted. For lamps of higher candle-power exceptional care has to be taken to ensure sufficiently good electrical connection between the lamp and its holder. Usually a modified form of the method illustrated in fig. 305 is employed, the essential difference being that substantial wires are attached to the platinum of the lamp, and then securely clamped in solid brass lugs on the under side of the holder. In large lamps, such as those of 500 candle-power, there are frequently a number of filaments, say five, each of 100 candle-power, joined in parallel. In the event of one breaking, the lamp is still of service, and, although its illuminating power is reduced, the electrical power absorbed is reduced in a corresponding degree. Lamps with long filaments, such as the 110-volt 16 candle-power lamp, should not be placed in a fitting where the filament would lie horizontally, or incline at an angle of 45° or less with the

horizontal, because of the tendency manifested by the filament to bend over towards the vertical position. Eventually a filament so placed comes into contact with the glass, and breaks. This tendency is, of course, a maximum where the plane of the filament is horizontal. The Edison & Swan Company manufacture a lamp which meets this difficulty admirably. The lamp contains two comparatively short filaments joined in series. In a 16 candle-power 100-volt lamp, for instance, there would be two 8 candle-power 50-volt filaments, of the simple U shape, fixed in the lamp so that their planes are parallel. The absence of the double loop and the shortness of the filaments render it all but impossible for the carbons to come into contact with one another or with the glass.

The 'life' of an incandescent lamp, or the number of hours that it can maintain illumination, varies considerably. Some filaments fracture in a few hours, while others will last for years, and we have seen one which, after burning steadily for at least 8,000 hours, was still giving a good light. It will be obvious that the life of the filament depends in a great measure upon the strength of the current which is sent through it. If a comparatively feeble current is employed, the lamp will last much longer than it would with an abnormally powerful one. On the other hand, the luminosity increases much more rapidly than the current strength, so that the question really resolves itself into one of comparative expense. A lamp that is burning low yields a much lower 'efficiency' but lasts longer than one of the same type which is brilliantly luminous; but it may be accepted, generally, that it is more economical to run lamps at a high than at a low efficiency. There are many lamps which last for several years, but which on account of their rapid fall in efficiency should be regarded as useless after only a few months' use. The vacuum for some reason or other deteriorates more or less in the course of time, while the carbon filament gradually becomes smaller and smaller, and the glass bulb rapidly diminishes in its transparency; and these are points which demand far greater attention than the substitution of some new material for the platinum leading in wires.

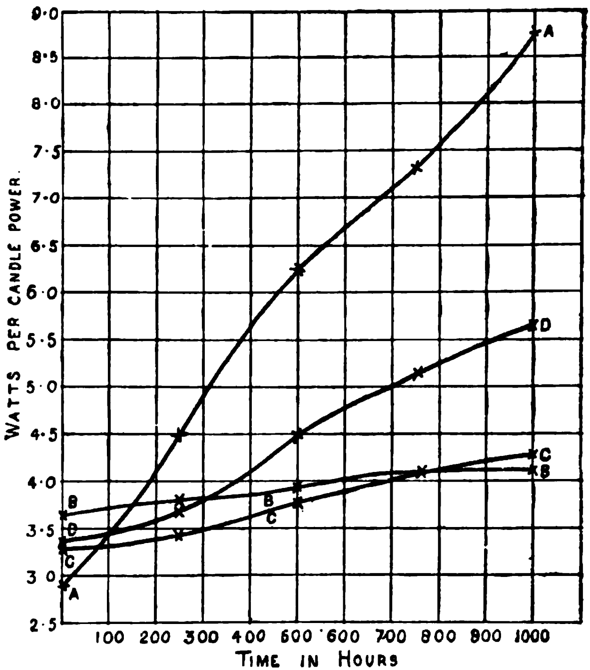
The efficiency of a lamp is frequently described as being proportional to the watts per candle-power—that is to say, to the ratio of the power absorbed to the light emitted—but it may

be more correctly referred to as the ratio of the light emitted to the power absorbed—that is say,

$$\text{Efficiency} = \text{candle-power per watt} = \frac{\text{candle-power yielded}}{\text{watts absorbed}}$$

The manufacturers claim that the best lamps in general use for ordinary lighting purposes absorb when run on a circuit of specified

FIG. 311.



voltage $3\frac{1}{2}$ watts per candle-power, so that the efficiency would be represented by $\frac{1}{3 \cdot 5} = 0{\cdot}2857$. This is about true for a new lamp, but after it has been running for a very short time there is frequently a decided falling off in the efficiency, and it is a good lamp which absorbs then only $3\frac{3}{4}$ watts per candle, or which has an efficiency of $\frac{1}{3 \cdot 75} = 0{\cdot}266$. Numerous experiments bearing

upon this point have been performed, but on account of the manufacture in England having been for so long in the hands of one company, the majority of the experiments have been made abroad.

Some important tests have been made by M. Ch. Haubtmann with our Edison-Swan lamps, and with several of the more important continental types. The lamps were of 16 candle-power, and made to run at a pressure of 102 volts. We have selected a few of the results, which are tabulated below :—

Type of lamp	No. of lamps under test	Hours	Candle-power	Amperes	Watts per effective candle
La Française	10	0	15·02	0·44	2·98
	10	250	10·00	0·43	4·38
(A)	9	500	7·01	0·43	6·25
	7	750	6·40	0·43	7·30
	7	1,000	5·08	0·43	8·70
Gabriel	10	0	18·00	0·63	3·57
	10	250	16·54	0·62	3·81
(B)	10	500	16·00	0·62	3·95
	9	750	15·40	0·61	4·04
	9	1,000	14·98	0·61	4·16
Edison-Swan	10	0	18·4	0·590	3·27
	10	250	17·5	0·590	3·43
(C)	9	500	16·0	0·585	3·73
	8	750	14·6	0·580	4·05
	8	1,000	13·9	0·580	4·40
Allgemeine Elektricitäts Gesellschaft	10	0	15·0	0·490	3·33
	10	250	13·3	0·485	3·64
	9	500	11·0	0·485	4·48
(D)	9	750	9·7	0·485	5·10
	8	1·000	8·8	0·485	5·61

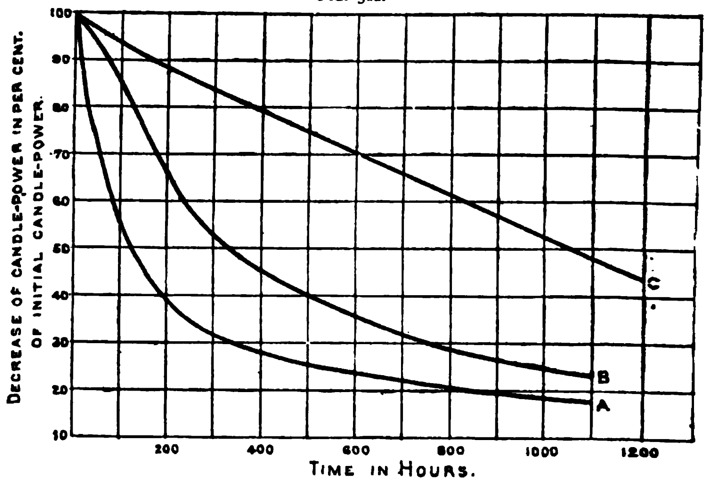
It will be noticed that in every case the test was commenced with ten lamps, and that some of every batch broke down before the expiration of the 1,000 hours.

The curves which we have constructed (fig. 311) from this table shows in a very marked manner the way in which the watts per candle rise as the time progresses, and it will be noticed that the English Edison-Swan lamp came out, on the average, as decidedly the most profitable lamp, while the lamps which started at the highest efficiency were after burning 200 hours by far the most unprofitable.

Of course, tests taken with only a few lamps cannot be accepted

as altogether conclusive; for, owing to the unavoidable variation in the durability of the filaments, one batch may give much better results than another, and one portion of a single batch may prove superior to the remainder of the same batch. The very fact that in no case did the whole ten of any single batch tested by M. Haubtmann last throughout the period of 1,000 hours, while, on the other hand, not a single batch was entirely destroyed in that period, demonstrates the necessity for a prolonged test of a very large number of lamps. Moreover, to be of any real utility the

FIG. 312.



lamps should be submitted to the same usage as that which they suffer in an ordinary installation, where the periods of lighting are intermittent and the voltage within certain limits variable.

There are several kinds of lamps in use which in their early days absorb only $2\frac{1}{2}$ watts per candle-power, but experience shows, so far, that such lamps have a much shorter life than those which are run at a lower efficiency; the transparency of the bulb rapidly deteriorates, while the filament loses in luminosity and soon breaks down altogether.

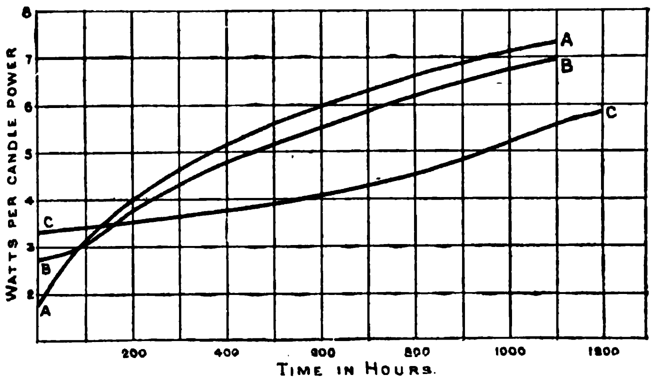
A long series of experiments was made by Mr. Clarence P. Feldmann in 1892. He used an alternating current with 50

alternations per second and a pressure of 72 volts. He tested 106 16 candle-power lamps of twenty-one different makes. The results obtained with Khotinsky lamps show the characteristic features of well-made 'low watt' or high-efficiency lamps. There were in all 18 lamps, which he divided into three groups, according to their initial efficiency :

Group A :	lamps giving	20·9	candles and	taking	1·72	watts per	candle.
,, B :	,,	16·66	,,	,,	2·76	,,	,,
,, C :	,,	16·0	,,	,,	3·32	,,	,,

The curves A, B, and C in figs. 312 and 313 show respectively the decrease in candle-power and the increase in watts per candle

FIG. 313.



for the respective groups. The following is a list of the casualties during the test of these lamps :

Group A

2 lamps were	broken	after	16	hours	1 lamp was	broken	after	246	hours
1 lamp was	,,	,,	45	,,	1	,,	,,	302	,,
1 ,,	,,	,,	130	,,	1	,,	,,	370	,,
1 ,,	,,	,,	176	,,	1	,,	,,	1,130	,,

Group B

1 lamp was	broken	after	110	hours	1 lamp was	broken	after	281	hours
1 ,,	,,	,,	212	,,	1	,,	,,	400	,,
1 ,,	,,	,,	246	,,	1	,,	,,	1,080	,,

Group C

1 lamp was broken after 370 hours | 2 lamps lived still after 1,500 hours.

It is thus shown that while some of the lamps of an initially high efficiency may last for a considerable time, the average life is short, and that they one and all deteriorate in luminosity and efficiency so rapidly that before 200 hours have elapsed they become inferior to the lower efficiency lamps of group C. It will be observed that the luminosity of group A fell 50 per cent. in 110 hours, of group B in 325 hours, and of group C in 1050 hours.

The results of the other tests showed that the above properties were common to all well-made lamps.

Mr. Feldmann has also constructed the following very instructive table based, in addition to his own experiments, on M. Haubtmann's and several other prolonged tests :—

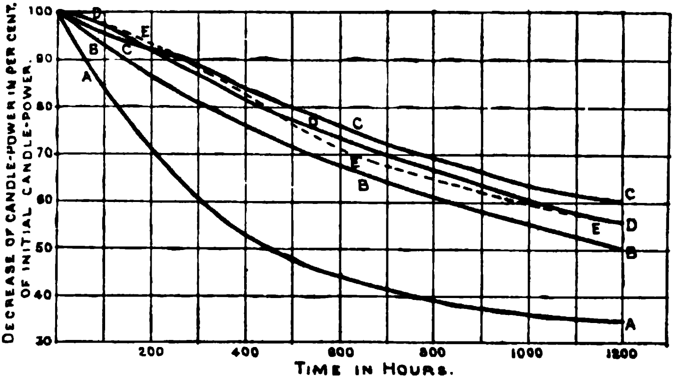
Table showing the Average Candle Power and Efficiency of Modern Incandescent Lamps at different periods of their lives

Time in Hours	Initial consumption 2·0–2·5 watts per c.p. A		2·5–3·0 watts per c.p. B		3·0–3·5 watts per c.p. C		3·5–4·0 watts per c.p. D		More than 4·0 watts per c.p. E	
	C.P. in per cent.	Watts per c.p.	C. P. in per cent.	Watts per c.p.	C.P. in per cent.	Watts per c.p.	C.P. in per cent.	Watts per c.p.	C.P. in per cent.	Watts per c.p.
0	100	2·4	100	2·9	100	3·3	100	3·8	100	4·5
100	84	2·8	93	3·0	95	3·4	96	4·1	96	4·7
200	70	3·3	85	3·3	91	3·5	91	4·3	92	4·9
300	59	3·7	81	3·5	88	3·6	86	4·5	87	5·2
400	53	4·2	76	3·8	84	3·7	81	4·7	82	5·4
500	48	4·6	71	4·0	79	3·9	77	5·0	75	5·8
600	45	4·8	67	4·2	76	4·1	73	5·3	72	6·1
700	41	5·2	64	4·4	72	4·2	69	5·6	68	6·4
800	39	5·3	62	4·7	69	4·4	66	5·9	65	6·8
900	38	5·5	59	5·0	67	4·7	63	6·1	62	6·9
1000	37	5·7	56	5·3	64	5·0	60	6·3	60	7·0
1100	36	5·7	53	6·0	62	5·4	58	6·5	58	7·1
1200	35	5·8	50	6·3	59	5·6	56	6·7	56	7·1

The table contains mean values for upwards of 500 lamps made in twenty-eight different factories, and the values given are plotted down in figs. 314 and 315. It is interesting to note that the lamps in column E, and curves E, which were of American manufacture and which have an efficiency of only 0·22, were less

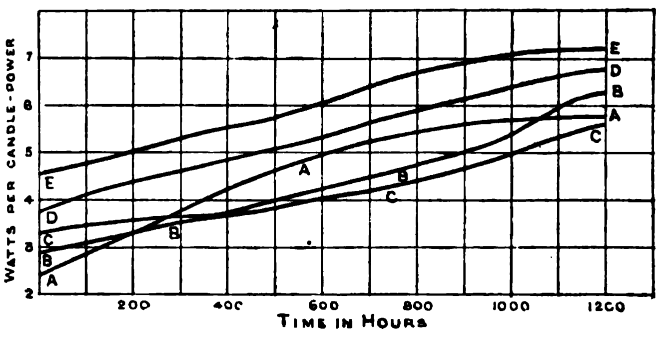
constant in luminosity than the lamps in C and D, having initial efficiencies of 0·3 and 0·26 respectively.

FIG. 314.



We might also add the results of a large number of other tests, but they are all in the main confirmatory in demonstrating that after about the first 200 hours running there is with high-efficiency lamps a rapid falling off in the luminosity accompanied

FIG. 315.



by a diminution in efficiency, facts which the student cannot have failed to observe by even the most cursory review of the figures

and curves. It will also be observed that the durability and efficiency of the lamps operated by an alternating current as shown in Mr. Feldmann's experiments correspond fairly well with those of M. Haubtmann, who employed a direct current for the purpose of his test.

In England the potential difference ordinarily supplied is 100 volts, the lamps in general use being run at from 4 to 5 watts per candle. This might appear to be an extravagant practice, but the filaments of 8 and 16 candle-power lamps are for this voltage undoubtedly very fine, and it has been pointed out that to run the lamps at 3 watts per candle it would be necessary to reduce the size of the filament so as to produce a decrease of illuminating surface to the extent of about 60 per cent. As we have already seen, very fine filaments are less durable than the more substantial ones, and it is therefore undesirable to push the incandescence too far—that is to say, to run the lamps at a high luminosity and therefore at an abnormally high efficiency. When this is done the saving in current may be more than counterbalanced by the destruction of the lamps.

The reduced transparency of the bulb to which we have already referred arises from a deposit of carbon upon the inner surface of the glass. This deposit increases with age, and is ascribed to a variety of causes.

The deposit on the glass not only reduces the transparency of the bulb, but it also involves a reduced section of the filament, the resistance of which is thereby increased. Such an increase in resistance means a feebler current and a much feebler state of incandescence. We thus see that much less light is emitted by the carbon, and that of this light a larger proportion is absorbed by the blackened bulb than would be the case with a clean one. The smaller current passing through the filament would, under ordinary circumstances, give a proportionally smaller reading at the meter, but sometimes the current taken by an old lamp is actually stronger than that taken by a new one.

Among the many experiments we have performed, the following are of considerable interest. Two 16 candle-power lamps were taken, one of them quite new, and the other an old one which we had been burning every evening, from sunset until

about 11 P.M., from December 1891 to March 1893. Both lamps were made for 110-volt circuits, and the tests were as follows :

—	Volts	Ampere	Watts	Candle power	Resistance hot	Resistance cold	Efficiency
New Lamp .	108·25	0·51	56·20	16·20	212·25	351	0·288
Old Lamp .	108·25	0·56	61·62	9·73	193·30	405	0·141

The inner surface of the bulb of the old lamp was very black, and there was a heavy deposit on the glass between the leading-in wires. There were thus two parallel paths through the lamp, one through the filament and the other through the deposit. Notwithstanding, therefore, the increased resistance owing to the diminished cross-section of the filament itself, the resistance between the lamp terminals was less when hot than that measured with the new lamp. The increased current, coupled with the diminished luminosity, reduced the efficiency of the lamp more than 50 per cent. A deposit such as we have here described is not often seen, the film being generally distributed over the more central positions of the bulb. Subsequently the old lamp was subjected to a potential difference of 160 volts, and after two minutes of intensely brilliant illumination an arc was established across the deposit between the leading-in wires, the bulb broke round the neck, and the filament fell away intact. A portion of the reduction in the candle-power of the old lamp was thus due to the blackening of the bulb and the shunting effect, and the remainder to the reduced area of the carbon ; for, as the resistance of the filament was increased, the current passing through it was proportionally reduced, and, as the heat varies with the square of the current, there is a rapidly increasing diminution in the light when the current falls.

During some American tests made by Professor Thomas, it was remarked that those lamps which were least blackened were of the makes which were advertised as exhausted by mechanical pumps, as opposed to the prevalent practice of completing the exhaustion by means of mercury pumps. All these lamps were very much alike in blackening, and only one-half as much blackened as the least blackened of the mercurially exhausted lamps ; and it has been contested that a considerable percentage

of the blackening in the latter case is due in some mysterious way to the condensation of the minute amount of mercury vapour assumed to be left in the bulb on its removal from the pump. But it is very doubtful whether a sufficiency of mercury is present, and, even were it so, it is questionable whether it would be competent to form a black film. It is certainly not established that the relative freedom from blackening in the mechanically exhausted lamps is due to the absence of mercury vapour in the lamps, as the makers claim, although if investigation should establish the claim the importance of the discovery can scarcely be overestimated.

It has been suggested that the deposit is due to the disintegration of the filament, and the collection of the carbon particles upon the surface of the glass. It is a very interesting feature that the deposit is not uniform, but is usually of greater density in the vicinity of the filament, as though the particles were repelled in straight lines on to the glass.

But it is difficult to satisfactorily account for the blackening on the hypothesis that by a species of molecular repulsion under the influence of the passing current, the carbon particles are expelled from the surface, and with sufficient force to drive them straight on to the glass. It is possible that during the process of flashing the somewhat dense and homogeneous incrustation of carbon which is deposited on the filament may imprison a number of atmospheric or other gaseous particles, which, on the passage of the current, become heated, and, finding no room for their natural expansion, make a vent by driving off the deposited carbon in a sort of miniature explosion, which has sufficient force to carry the disintegrated particles as far as the glass. It has, however, been observed that lamps made with filaments which have been carbonised at a comparatively low temperature blacken very readily, whilst when made with others which have been raised to a very high temperature they resist the tendency very much more effectually. This is probably due to the fact that the filament carbonised at a high temperature is purer and more dense than those which have not been heated so intensely. The same results have also been observed to occur in lamps when low or high temperature flashing has been employed. These

facts tend to prove that the blackening is due to a partial volatilisation and re-condensation of the carbon particles. Certainly the temperature of the incandescent filament—about 2,000° C.—is lower than that already ascribed to the positive carbon in the arc ; but this discrepancy may to some extent be very plausibly accounted for by the fact that in the incandescent lamp there is no air pressure, and that this absence of pressure may lower the temperature of volatilisation, just as an increased air-pressure on the arc so alters the condition of affairs that a much higher E.M.F. becomes necessary in order to maintain the arc consequent upon the increased temperature of volatilisation. If this be the true explanation of the blackening phenomenon, it follows that the difference in degree between the filaments prepared at low and high temperatures respectively, must arise solely from the circumstance that a comparatively loose condition of the carbon is especially favourable to the formation of carbon vapour. On the other hand, we can conceive that the readiness with which a filament could be disintegrated, or could suffer loss by the chemical action of some impurity remaining in the lamp, would vary inversely as its density. The film, by whatever process it may be formed, is apparently pure carbon, as it is a sufficiently good conductor to take a continuous coating of copper when placed in an electrolytic bath.

If the blackening of the bulb were due to the simple breaking away of the carbon particles, then we might imagine that the durability of the lamp would be materially less on an alternating than on a direct current circuit, because of the constantly varying conditions to which the filament would be subjected. But the tests to which we have already referred tend to show that a lamp on an alternating circuit is as efficient and durable as when placed in a direct current circuit, and the fact that it only blackens at about the same rate tends rather to demonstrate that the loss of carbon by the filament must be ascribed to volatilisation.

The coating deposited by a given filament on a large bulb would, in a given time, be less dense than on a smaller bulb, because a given number of particles would be deposited over a larger area, but it is questionable whether this would affect the luminosity. The filament gives out a definite number of luminous

rays, which are more or less intercepted by a definite number of carbon particles, and the total absorption would probably be the same whether the film be large and thin or small and dense.

To show the effect of the carbon film, an experiment is recorded in which an old filament was removed from its bulb and transferred to a new one, when the light emitted and measured under similar conditions, showed an increase of 15 per cent. In this case, however, the degree of exhaustion may have been, and probably was, different, and it is difficult to guarantee absolutely uniform transparency in a number of bulbs, so that the importance of a test of this kind might easily be over-estimated.

It was for a long time erroneously supposed that the great object to be aimed at in making an incandescent lamp, was to make its 'life'—that is to say, the period during which it could emit light—as long as possible. The tables and curves already given will doubtless have made it evident that the continued efficiency of a lamp is of far greater importance than its life, even when the price of the lamp is high.

M. André Larnaude, as the result of tests carried out in the laboratory of the Compagnie Générale des Lampes Incandescentes, estimates that the life of a lamp increases much more rapidly than its efficiency decreases, and concludes that lamps run so as to absorb

2·5	watts per candle,	last for	150	hours
3·0	,,	,,	350	,,
3·5	,,	,,	700	,,
4·0	,,	,,	1,000	,,

Very different figures are, however, given by Messrs. Siemens and Halske, of Berlin, whose experiments tend to show the following to be the duration of 16 candle-power lamps :

1·5	watts per candle,	last for	45	hours
2·0	,,	,,	200	,,
2·5	,,	,,	450	,,
3·0	,,	,,	1,000	,,
3·5	,,	,,	1,000	,,

When incandescent lamps are being run on a constant potential circuit—that is, when they are joined across the mains in

parallel—their resistances, if they are all of the same candle-power and efficiency, must be uniform, so that they will take the same current strength; but if lamps of different candle-power are to be employed on such a circuit, then their resistances must vary inversely as the currents they are to carry, that is to say, inversely as their required candle-power. For example, an eight candle-power lamp should require only half the expenditure of electrical energy that should be necessary with a 16 candle-power lamp. Now the electrical power expended in a lamp (or the number of watts) is proportional to the potential difference multiplied by the current strength. If, therefore, we represent the electrical power in watts by W, the pressure in volts by E, and the current in amperes by C, then $W = EC$. But E is constant, therefore if W for a 16 candle-power lamp is twice as much as for an 8 candle-power lamp, R in the former case must be half as much as in the latter. Let us suppose that we have a 100-volt circuit, and that a 16 candle-power lamp takes 60 watts, also that an 8 candle-power lamp takes 30 watts, then for the former

$$W = EC$$
$$= 60 = 100 \times 0{\cdot}6$$

and for the smaller lamp

$$W = EC$$
$$= 30 = 100 \times 0{\cdot}3$$

But by Ohm's law, $R = \frac{E}{C}$, and for the 16 candle-power lamp

$$R = \frac{E}{C} = \frac{100}{{\cdot}6} = 166 \text{ ohms.}$$

Similarly for the 8 candle-power lamp

$$R = \frac{E}{C} = \frac{100}{{\cdot}3} = 333 \text{ ohms.}$$

The obvious meaning of this is that, for a given voltage and for a given make and length of filament, the higher the illuminating power which a lamp is required to yield the thicker must the filament be. If the filament suitable for a 16 candle-power lamp on a circuit of given voltage were halved, and the halves placed in separate bulbs, each would give a luminosity of approximately

8 candle-power, providing that the two lamps were placed in series. If one of them were joined direct across the mains, the current that would flow through it would be twice the normal strength, and the filament, being unable to support such a current, would break. The resistance of carbon falls somewhat rapidly with an increase of temperature, so that the resistance of a 16 candle-power 100-volt lamp is more than 300 ohms when cold.

When we have once established a fair average efficiency it becomes a very simple matter to estimate the amount of light obtainable from a given electrical power, or, conversely, the power that would be required to maintain a given number of lamps. On the basis of $3\frac{3}{4}$ watts per candle, a 16 candle-power lamp taking 60 watts would on a 60-volt circuit require a current of 1 ampere, and on a 100-volt circuit 0·6 ampere.

If we have an available potential difference of 100 volts and a current of 60 amperes, we have a total power of 6,000 watts, which—ignoring, for the time being, the resistance of the mains—would suffice to maintain a hundred 16 candle-power lamps, or fifty 32 candle-power lamps. Or if we require to light two hundred 16 candle-power lamps at 100 volts, then we must provide a current of 120 amperes. It is almost unnecessary to say that every lamp is made to run at a given or definite voltage, and that it would be quite impracticable to place the same lamp indifferently on a 50 and on a 100 volt circuit. The voltage that the lamp will require is determined by the dimensions of the filament, and every filament is so dimensioned as to yield its standard luminosity at the highest temperature compatible with durability, and any material increase upon that temperature would tend to cause volatilisation and consequent rupture of the filament. When lamps are slightly over-run—that is to say, when the voltage applied is slightly above the normal (say 2 volts) and when therefore the current is also abnormally high—the increase in luminosity is considerable. If the lamp could sustain this, it would of course be very advantageous, but, as we have already seen, the lamps would under such circumstances soon give way.

A 16 candle-power lamp made for a pressure of 100 volts yields at 95 volts about $12\frac{1}{2}$ candle-power, and at 105 volts about

$22\frac{1}{2}$ candle-power, so that the luminosity increases much faster than the volts, and experiment appears to indicate that the candle-power of a given lamp varies roughly as the sixth power of the voltage applied, and as the cube of the watts absorbed. When the illumination is reduced to about one half of its normal amount, the power absorbed in the filament is reduced by only 20 per cent. or thereabouts.

It is, therefore, a false idea of economy to imagine that by under-running an advantage will be gained. A reduction of only two volts makes itself very apparent in the amount of light emitted by the filament, and although it will probably result in a prolongation of the life of the lamp, the advantage thus accruing is more than neutralised by the reduced efficiency. In such a case the luminosity obtained will, even with a new lamp, be at a cost of more than four watts per candle-power. Although there is a considerable saving involved in the prime cost of mains and conductors by using high voltage lamps, there is a limit to which this saving can be advantageously carried. An 8 candle-power lamp, for instance, when constructed for a circuit of 100 volts, must have a very thin filament in order that it shall offer sufficient resistance to allow only 30 watts or thereabouts to be expended upon it—that is to say, to allow about one-third of an ampere to flow through it—and it should be evident that with such a thin filament the loss of carbon would more rapidly involve a complete rupture than when a thicker filament is employed. Where 8 candle-power lamps are extensively used, it is therefore preferable to place them on, say, a 50-volt circuit, or to join two of them in series across a pair of mains having a potential difference of 100 volts.

It must be remembered that, however large the main conductors may be, they must offer some definite resistance to the current, and must therefore involve, between the machine and the lamps, a certain loss of potential. Let us suppose, for example, that a large room at the limit of the circuit takes a current of 50 amperes and that the resistance of the conductors between the machine and the switch is 0·04 ohm, then the loss of potential in those conductors will be $E = C \times R = 50 \times 0{\cdot}04 = 2$ volts. Hence a lamp on the dynamo itself would be run at a potential difference of, say, 112 volts, while a lamp in the distant room would have only 110

volts. It is the practic in good installations to allow a maximum fall of potential between the dynamo and the farthest lamp, when all lamps are in circuit, of 2 volts. When the wiring is improperly done, the fall is frequently much higher, and we have come across many cases where it is as much as 8 or even 10 volts. The energy which thus fails to reach the lamps is, of course, wasted in heating the conductors. Such badly proportioned mains are prejudicial in another way. When only a small proportion of the lamps is in use they will receive almost the full pressure of the machine, and in cases where it is the practice to over-run the dynamo in order to compensate for the loss in the mains, the life of the lamps may easily be shortened by having too strong a current forced through them. The loss in the mains is easily calculated, as the fall of potential at full load is equal to the maximum current multiplied by the resistance, and the power lost is equal to this fall of potential multiplied by the current.

Assuming an efficiency of 3·5 watts per candle, it follows that 746 watts, or one electrical horse-power, expended in the filaments would produce a light of 213 candle-power, an equivalent to that of thirteen 16 candle-power lamps. But the power developed by the engine is frittered down by the losses in the dynamo, the leads, and the fittings, so that, in practice, not more than ten 16 candle-power lamps can be maintained for each horse-power developed by the engine.

If we assume that each lamp will be made to last 1,000 hours, and it will be a long time before the consumer can be taught to see the advantage of more frequent renewals, then, on a basis of an average of two hours burning per day, the whole of the lamps in an installation would have to be renewed at the end of about eighteen months, so that a 50-lamp installation would cost nearly 3*l.* per annum for lamps alone, and this is an item of sufficient importance to have some considerable value in determining whether or not the light shall be adopted.

When a number of ordinary incandescent lamps are joined in series, the fracture of the filament in one lamp involves the extinguishing of the other lamp or lamps in series with it. If, therefore, all the lamps in a circuit were joined in series, the failure of one lamp would result in a total disconnection of the circuit. The

parallel system has many advantages. There is no risk of receiving a serious shock on touching the mains, as the total potential difference is only that necessary for one lamp, which rarely exceeds 100 volts or thereabouts. If one of the branch leads should become broken, only the lamp on that branch will be thrown out of use. The means available for connecting the lamp to the supply wires are of the simplest description. The insulation of the mains is a matter of less difficulty than with high potential circuits.

On the other hand, the cost of the mains in a large installation is considerable, for massive conductors must be employed, otherwise their resistance would be so high as to cause a serious waste of electrical energy in overcoming that resistance. It needs also to be added that the maintenance of a constant potential difference throughout an extensive network of wires is a matter of some difficulty, a difficulty which does not attend series working.

Lamps constructed for series working—that is to say, on a constant current circuit—are usually provided with low resistance filaments, designed to carry a current of 5 or 10 amperes, and can therefore be joined up in circuit with ordinary arc lamps. Under some circumstances this is a decided advantage; for example, in cases where an arc lamp would at certain hours give more light than is required (and would then involve a waste of energy), but where total darkness is undesirable, a series incandescent lamp can be joined with an arc lamp to a 'two-way' switch, by turning which either the arc or the incandescent lamp can be thrown in circuit at will, both lamps being constructed to take the same current. Of course the volts, and therefore also the watts, required for the incandescent lamp would be considerably less than in the case of the arc lamp. Again, when an ordinary lamp is used in series on a high potential circuit, a fracture of the filament sets up a small arc, which, being sustained, consumes the materials of the lamp, and, even if no further damage ensues, it causes a disconnection of the circuit.

Several good series lamps have been devised, one of the chief difficulties to be met being the provision of an automatic cut-out which shall act promptly when the circuit through the lamp is broken, and short-circuit it. An interesting lamp constructed for

series working is that of Mr. Alexander Bernstein. The filament is composed of a slender carbon tube, made by carbonising a silk braid of fine texture, and it is remarkable that the fine threads composing the braid are distinctly discernible in the finished filament. Fig. 316 illustrates the construction of the lamp, in which the straight carbon tube or filament *a* is supported by pieces of iron wire $b\ b_1$, their lower extremities being connected to the short pieces of platinum fused through the bottom of the bulb. These wires, $b\ b_1$, are bent in such shape as to almost touch each other at *c*. They are also furnished with sleeves of insulating material $d\ d_1$, connected together by a spiral spring *e* which strives to draw them together. As long as the carbon is intact, its rigidity prevents contact between *b* and b_1 at *c*, but as soon as a flaw in the carbon appears the current commences to destroy it, and the spring *e* draws the wires together, until a perfect contact is produced at *c*, and then a short-circuit is obtained inside the lamp. It will thus be seen that on the extinction of one lamp by the fracture of its carbon, the circuit for the other lamps is automatically completed.

FIG. 316.

In another form of this lamp the spiral spring is dispensed with, a portion of one of the iron wires being hammered out flat, and a slight springiness imparted to it, so that on the carbon being broken continuity is re-established at *c*.

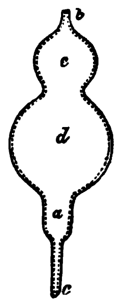
The manufacture of the bulbs for 'loop' lamps is comparatively a simple matter, but with lamps having a rigid rod or tube, such as the Bernstein, the case is very different. This will be evident when it is observed that the length of the carbon is considerably greater than the diameter of the neck of the bulb; with the ordinary bulb, the insertion of the mounted carbon would therefore be a matter of impossibility.

The method of making the Bernstein bulb is very ingenious. Two bulbs, *e*, *d* (fig. 317), are first blown in a piece of glass tubing *b c*; the end *b* is then broken off, and the bulb *e* being heated, it is

worked into the form of an open cylinder. The carbon and the connecting wires, fixed in a glass stem, are then introduced through the large opening thus made, this opening being then closed, so that only one bulb remains. The next operation is to weld a piece of small tubing to the top of this bulb, after which the small tube *c* at the bottom is broken off, and the stem, with its connecting wires, dropped through and fused into position. The next performance is to exhaust the lamp by way of the little tube fused on to the top, and that being completed, the bulb is sealed off and fixed into its socket.

In order to prevent the interruption of the circuit by the removal of a lamp, its holder is constructed in such a way that the lamp can only be withdrawn from it if a short-circuit has been made in the holder beforehand; and, furthermore, as this short-circuit can only be broken after the lamp has been placed in position, it is not possible to disconnect the circuit at the holder.

FIG. 317.



The electro-motive force required by the Bernstein lamp ranges from 4 to 15 volts according to the luminosity, which usually ranges from 16 to 50 candle-power. The normal current strength required is 10 amperes. On account of the small mass of carbon in the hollow filament, these lamps are very efficient, and it is claimed that with lamps of from 32 to 50 candle-power the consumption of electrical energy is at the rate of only 2·75 watts per candle.

Bearing in mind the peculiar advantages which the series system of lighting by incandescent lamps undoubtedly possesses, it is somewhat surprising that so little attention has been given to it. Practically the only English worker who has seriously and persistently pursued the subject is Mr. A. A. Goldston. His great object has been to develop a workable system for lighting streets and open spaces by means of incandescent lamps as opposed to arc lamps; and for streets of secondary importance, incandescent lighting is certainly more economical, and may be rendered even more effective. With the parallel system, there is not only the question of the mains to be considered, but also the rapid fall in the luminosity of the lamps consequent upon the reduced current

through the filament and the reduced transparency of the bulb. On the other hand, with series lamps, the current strength is maintained under all conditions, and any slight reduction which may take place in the area of the filament tends to increase the luminosity and thereby to compensate for the blackening of the bulb. This makes but little difference in the life of the lamp, while its luminosity is practically uniform throughout its life. It is of course essential to provide a cut-out device, and one advantage pertaining to the lamp about to be described, is that the lamp itself contains the filament only, the short-circuiting arrangement being entirely separate.

FIG. 318.

It has the further advantage that the operation of the cut-out does not in any way injure it, whereas in some other cases where external cut-outs have been attempted, the short-circuiting is accompanied by the destruction of the cut-out. Fig. 318 illustrates Mr. Goldston's lamp, together with its holder and cut-out device.

The lamps themselves are made of various illuminating powers, the particular one illustrated having been constructed to yield a light of 50 candle-power, which at 2·25 watts per candle involves an expenditure of 112·5 watts. The strength of the current being

10 amperes, the fall of pressure is 11·25 volts. A filament, in order that it may withstand such a comparatively heavy current, must of necessity be considerably thicker than the filaments employed in lamps absorbing an equal power at the higher pressures obtaining on parallel circuits. The entire length of the filament proper is but two inches, so that, although the sectional area of carbon is increased, the illuminating surface is practically the same as in the corresponding constant potential lamp. The ends of the filament are connected to a pair of comparatively long iron wires, which in their turn are connected to the platinum loops fused through the top of the glass bulb. In all lamps of high candle-power a great amount of heat is developed, and it becomes difficult to prevent the temperature and consequent expansion of the platinum increasing faster than that of the glass. Where this is allowed to happen, the platinum frequently cracks the glass and thereby impairs the vacuum. In the lamp under discussion the difficulty has been overcome, in the first place by interposing between the filament and the platinum loops stems of iron, a metal which is, compared with, say, copper, a poor conductor of heat; and, secondly, by affording unusually good facilities for the dissipation of heat at the lamp terminals, which consist of small copper strips, securely fixed to the platinum loops by means of miniature bolts and nuts. These strips, when the lamps are placed in position, are each clamped in a split terminal, to the other end of which a bare flexible lead is attached. Each of these flexible conductors passes through a hole drilled in a phosphor-bronze contact-piece, to which the conductor is firmly secured, both mechanically and electrically, by means of a set screw.

The end of the conductor, after passing through the contact-piece, is connected directly to one or other of the V-shaped brackets which also carry the main terminals. The phosphor-bronze contact-pieces are pivoted on links and levers, which constitute a parallel motion. The spiral springs seen in the figure pull at the ends of the levers in such a manner as to urge the faces of the contact-pieces together. When they actually make contact, they short-circuit the lamp, so that the whole of the main current then passes through them, and under such circumstances ample and reliable contact is essential. This is ensured by employing

large contact surfaces in conjunction with the parallel motion which allows practically the whole of those surfaces to make good contact, either when both levers move together or when only one moves. Normally these contact pieces are kept apart and the current allowed to flow through the lamp, by the application of the requisite amount of tension on the stranded conductors. This is effected by a very ingenious yet simple device. A light glass stem is sealed on to the bottom of the bulb, the lower extremity of the stem being slightly thickened to enable a light coarse screw ferrule to be securely cemented to it. A loosely running nut carried by the stiff wire bow engages with this ferrule and enables the amount of tension necessary to pull down and separate the phosphor-bronze contact-pieces to be applied. The supporting brackets are mounted on a teak base, the bow and reflector being also insulated from the lower ends of the brackets by thick mica washers in the union nuts. Obviously, in the event of any mechanical injury to the lamp, the tension is released and the springs immediately force the contact-pieces together. The same thing happens in the event of any accident to the interior of the lamp. If, for example, the filament breaks while the lamp is running, an arc is established across the break, and, travelling up the iron stems, either fuses them, and thereby allows molten metal to fall upon the bottom portion of the bulb, where it will cause a fracture and separate the light glass stem from the rest of the bulb, or failing this the arc will travel up to the crown of the bulb, and cause a fracture there. In either case the tension is released and the lamp short-circuited. The light glass stem is so proportioned and fixed that while it can withstand a considerable direct pull, it will certainly break under any mechanical shock which would be sufficient to break the filament. The lamp and its fittings as illustrated are suspended inside a weather-tight lantern fixed on the top of an iron post, and it will be observed that in any case the only part to be renewed is the lamp, the safety device remaining intact and ready for use on the insertion of another lamp.

Incandescent lamps are serviceable in a variety of ways. For domestic lighting they, although in most cases in England somewhat more expensive than gas, know no equal. They in no sense of the word vitiate the air, nor do they consume it; they have

very little effect upon the temperature of a room; they are not injurous to furniture, books, or ceiling, and deposit no soot; they can be placed near curtains or other combustible materials without entailing any risk of fire; they are independent of air currents, which cause flickering in any lamp where gas or oil is burned; they are exceedingly convenient, and can be 'turned on' at any moment without necessitating the use of a match; the tap or switch for turning them on can be placed in any convenient position; and the lamps are incompetent to cause explosions, because the filament is destroyed immediately the bulb is broken. On the other hand, they consume a practically invariable amount of energy, for the light cannot be turned down without the introduction of a shunt, or of resistance, in which the energy which would otherwise be absorbed in the lamp is expended. They are, however, unsatisfactory for street lighting unless of high candle-power, for most of the advantages which pertain to them when used in a house disappear when they are taken into the street. The public look for a brilliant light and get only the equivalent of a good gas jet, and have to pay dearly for the luxury. They are exceedingly adaptable to the lighting of railway carriages. They have no equal for ship-lighting, their usual competitors in such cases being bad oil and worse lamps. In the case of passenger steamers expense is not of paramount importance; hence it is not to be wondered at that in this work incandescent electric lighting now reigns supreme. Incandescent lamps should prove of inestimable service in mines and in the bunkers of ships, where the chief difficulties to be contended with are want of portability, and the risk of sparking between the broken ends of a wire, or at switch contacts. These are matters which must soon be conquered, and there is but little doubt that before long the Davy and Geordie 'safety' lamps will be relegated to historical museums. There is a scope for incandescent lamps for the use of divers, and in many surgical examinations and operations, as well as for the microscope and the optical lantern.

In order to estimate the amount of light emitted by any luminous source, electric or otherwise, a large number of 'photometers' or light-measurers have been devised, but excellent as some of these may be in theory, they have, when applied practically, two

serious defects. Measurement of every kind requires some unit or standard with which to compare the substance, force, or effect it is desired to measure; and it is pre-eminently essential that this unit or standard shall be fixed and invariable, and that it shall, without very much trouble, be reproducible. The majority of units comply more or less with these requirements; the one unit which does not, which is never fixed, but is always liable to variation, is the so-called unit of light. With us in England, the official unit is the 'candle-power,' which is assumed to be the light produced by a 'standard candle' weighing six to the pound and made to burn 120 grains of spermaceti wax per hour. The length of the candle varies slightly with different makers, ranging from $8\frac{1}{4}$ to 9 inches, measured from the shoulder, where the diameter is about 0·8 in., the diameter at the bottom increasing to 0·85 or 0·9 in.

In practical work a straight candle is selected and cut into two equal parts, which are subsequently used together on a short bar placed at right angles with the scale-bar of the photometer. The two flames give a more reliable, or better average, result than a single one. Candles are lighted ten minutes before the commencement of testing so as to allow them to arrive at their normal rate of burning, which is shown when the wicks are slightly bent over and the tips glowing. In fixing them in position, the plane of curvature of one wick should be at right angles to the plane of curvature of the other. If the candles are used when the wicks are straight, or when a little knob or rose of carbonised thread has formed at the tip, the tests will give erroneous results.

The special requirements of a standard flame are that the combustible must be of known and definite composition; the conditions of burning must be of a simple and definable character, and the nature of the combustible, as well as the conditions of burning, must be such that atmospheric changes may produce a minimum effect upon the light.

Now white spermaceti has a melting-point of 109°, but a small quantity (varying from four to five per cent.) of beeswax with a melting point of 140° is usually added in order to prevent the crystallisation of the spermaceti. The spermaceti itself is not a definite chemical substance, its constituents varying considerably; whence it fails to answer the first requirement, for the consequence of the differences

in the proportions of the natural and added constituents is that small variations are found to occur in the melting-point.

The number and size of the threads in the wick, its chemical treatment, the closeness of the plaiting of the strands, and the degree of tightness with which the wick is stretched, are also conditions which affect the light of a sperm candle, yet they are all left undefined by the Acts of Parliament; and, in practice, manufacturers differ in regard to them.

Even were the candles made as exactly alike as possible there are other conditions of variation which cannot be eliminated. For instance, the light varies from moment to moment as the wick bends over, as the knob at the end of the wick accumulates or burns away, and as the cup fills or empties itself of melted sperm.

A number of experiments made by a Committee appointed by the Board of Trade showed that while the candles from a single packet gave fairly concordant results, the average obtained by ten experiments with one packet differed as much as 15 per cent. from the average obtained by ten experiments with another packet. In 115 determinations a maximum variation was found between two pairs of candles of 22·7 per cent. in illuminating power. All these experiments were made by one observer, working with one set of apparatus and in the most uniform manner possible.

The method of taking the average of three consecutive candle determinations does not therefore serve to eliminate the errors of the candle standard, for the candles employed may be taken from a packet containing candles of a uniformly high or a uniformly low illuminating power.

Standard candles are greatly affected by slight differences of treatment, so that a candle which gives a certain amount of light in the hands of one operator, may give a widely different result when used by a second operator.

The extreme sensitiveness of standard candles to differences in treatment is shown by the following typical experiment. Four official gas examiners tested on the same day a specially stored sample of coal gas. They used the same photometer, and candles from one packet selected for the uniformity of the candles contained in it. The mean of two closely agreeing tests by one examiner gave the illuminating power of the coal gas as 16·5

candles, while the mean of two closely agreeing tests by another gave the illuminating power of the coal gas as 19 candles.

Mr. J. W. Dibdin has reported very adversely upon the standard candle. He found on one day that the average of the tests with candles made by one firm (A) showed the illuminating power of a certain gas flame to be equal to 15·8 candles, while candles manufactured by another firm (B) gave a value of 14·9 candles; on another day candles A gave a value of 14·8 to a constant gas flame, while candles B gave a value of only 12·9.

It can, therefore, be readily conceived that a total variation of 10 per cent. is almost a normal result, while far greater differences are of common occurrence.

Another cause of unreliability under certain conditions is that when the temperature of the testing room rises above the normal the candles invariably give discordant results, sometimes indicating over 25 per cent. more than the known value of the comparison flame. The principal cause of variation is, however, the varying form and variable structure of the wick, which at one time had eighteen threads in each of its three strands, while at the present time the number has increased to twenty-one and twenty-three. Various improvements have been effected in the processes for 'drying' the spermaceti, or freeing it from oil, and the drier spermaceti now manufactured seems to require a wick containing more threads of cotton to raise it in the melted form and cause its combustion at the required rate of 120 grains per hour. But candles with thick wicks give less light than those whose wicks are thinner. Thus the effect of the improvement in the manufacture of spermaceti has been that standard candles give less light now than they gave ten years ago, and probably still less than they gave at an earlier date, when the average consumption of candles of six to the pound was 140 grains per hour.

A further very apparent objection is that the illuminating power is subject to fluctuations from minute to minute, owing to variations in the length and form of the wick, and to the filling and emptying of the cup of the candle, according to the movements of the surrounding air.

Sufficient has been said to make manifest the imperfections of the spermaceti candle as a standard.

One of the sources of error, viz. the irregular consumption of the spermaceti, can be to some extent allowed for by weighing the candle before and after the tests are made, the time of burning being also noted. If the consumption has not been at the exact rate of 120 grains per hour, the light emitted should be deemed proportionately different in intensity, and the measured intensity of the light as observed by the photometer should be accordingly increased or diminished in the same proportion by a simple rule-of-three calculation. Thus if a lamp has been measured by the apparatus as giving a light of 17 6 candles, but the candles have been burning at an average rate of 116 instead of 120 grains, it follows that $120 : 116 :: 17{\cdot}6 : x = 17{\cdot}01$. A delicate balance is supplied with the better class of photometers, by means of which the rate of consumption can be readily ascertained.

In Germany a standard paraffin candle is employed, but no better value can be attached to it than to the spermaceti candle. The amyl-acetate lamp affords a more accurate and reliable substitute for the standard. The lamp is very simple, and carries a wick saturated with amyl acetate, which is so adjusted that the flame reaches a certain height. It has, however, the objection that the flame is too rich in red rays, a fact which considerably reduces its utility when white light has to be measured.

The French sometimes use a stearine candle as a standard, but the actual French official standard is the 'Carcel' lamp, in which purified colza oil is consumed at the rate of 42 grammes per hour, and in which, of course, a wick is employed. The wick is cylindrical in shape, and gives, therefore, an 'Argand' flame. It should be woven with 75 strands, and weigh 3·6 grammes per decimetre of length. The chimney is 29 centimetres in height, its diameter being contracted at a short distance above the wick, from 47 to 34 millimetres. A good white light is produced, but from what has been said when discussing candles it will be evident that, for making exact tests, extreme care must be exercised in the manufacture and use of the lamp and the combustibles. The chemical composition of the oil is liable to variation, and the simple fact that a wick is employed opens the way to a host of irregularities. It is, however, less affected by air currents, &c., and is

preferable to a candle. The standard Carcel is computed to be equal to about 9·5 standard spermaceti candles.

Several other attempts have been made to provide an efficient substitute for the standard candle, among them that of M. Violle, who at the Paris Congress in 1888 proposed as the standard of light that which is emitted by a square centimetre of melted platinum at the temperature of solidification. This would be a very inconvenient standard, and is also objectionable on account of the difficulty of obtaining absolutely pure platinum. It will be remembered that it was in Chapter XV. pointed out that the light from the crater of a fully developed direct-current arc is constant so far as the intrinsic brilliance is concerned. This fact was ascertained by Captain Abney, and it has been proposed to adopt as the standard, the light emitted from a square millimetre of the crater of the arc formed between a pair of pure carbons. One difficulty in connection with the proposed standard is that of obtaining absolutely pure carbon, and the suggestion, although a very good one, has not met with a very hearty response. The only suggested substitutes which may now be said to remain in the lists are the Methven screen and the Harcourt air-gas flame.

The 'screen' invented by Mr. John Methven is an exceedingly simple piece of apparatus. The instrument as now constructed by Messrs. Wright & Co. is illustrated in fig. 319, and consists of an upright rectangular metallic plate or screen, having attached to its lower edge a horizontal flange or bracket, which supports a standard London Argand gas-burner. This burner is supplied with gas through a plug or nosepiece projecting downwards below the flange. In the screen, above the level of the burner, there is a hole or slot which is covered by a thin silver plate, having a small vertical slot of such dimensions as to allow of the passage of just as much light as equals that afforded by two average standard sperm candles, when the gas consumed is sufficient to yield a flame three inches in height. It will be seen from the figure that a glass chimney is employed; it measures 6 inches high by 2 inches in diameter, the supply of gas necessary to produce the required flame being controlled by a tap, or, in the better class of instrument, by a micrometer cock capable of very fine adjustment. The two horizontal wires attached to the back of

the screen, one on either side of the chimney, are placed at the requisite distance above the burner, and serve the purpose of determining when the prescribed flame length has been obtained. The apparatus is sometimes used with the richer pentane vapour as the illuminant (reference to which will be made presently). In such cases a second silver plate and slot is provided, of reduced dimensions, and furnished with a pair of horizontal wires $2\frac{1}{2}$ inches above the burner, to which height the flame must be adjusted.

FIG. 319.

The Methven screen has the advantage that it forms a reliable and practical standard, easy to manipulate and not likely to get out of order. Its simplicity of construction as well as of manipulation is self-evident, and its suitability for the required object has been demonstrated by Mr. F. W. Hartley, who made a great number of tests with the apparatus, using slots of various dimensions. In one set of tests he found that with a 5 cubic feet per hour flame, of common coal gas of 14·02 candle-power, the difference in the photometric readings between a 3-inch Argand flame from the same gas and from cannel gas of 35·37 candle-power was only 0·7 per cent. These experiments tend to show that it is the height of the flame rather than the quality of the gas consumed which determines the luminosity, and this is a most

important point, for it renders the standard virtually independent of any ordinary variations in the composition and lighting properties of the gas. A series of experiments was next made with standard candles which were employed to measure the light emitted by the common gas; the readings ranged from 13·24 to 14·588 candle-power, showing a difference of 1·348 candle, or 10·11 per cent. As these tests were made with gas supplied from the same holder, the result simply re-proves the utter unreliability of the standard candle. On the other hand, when the Methven screen was employed, the two kinds of gas being consumed in turn, the extreme difference was 0·83 per cent., and the mean difference 0·3 per cent. only.

While it is of course necessary that the height of the flame should be carefully adjusted, it is an important feature that the readings are not perceptibly affected by a variation of about one-tenth of an inch on either side of the prescribed height. The top of the flame should be as regular as possible, the burner of the best manufacture, and the chimney and screen scrupulously clean. As, however, it rarely happens that the top of the flame is absolutely regular, it is usual to so adjust the height that the extreme points extend about one-eighth of an inch above the horizontal wires. There is one other precaution, and that is, that the instrument should be allowed to get 'hot,' so as to arrive at the normal condition, before any reading is taken on the photometer. If this is neglected, erroneous results are almost inevitable, as the proportion of energy absorbed in heating the apparatus will be a varying quantity. However, this only entails a delay of about five minutes after the gas is lighted.

It is scarcely to be wondered at that a standard so nearly approaching perfect uniformity in its indications, and so simple in construction and manipulation, should have found considerable favour in the electrical industries, where it is almost exclusively employed. To put the matter in a few words, it is a practical piece of apparatus. As Parliament has not yet prescribed any particular luminosity for electric lamps, manufacturers of electrical apparatus, and those supplying electricity, are not, like gas companies, tied down to the sperm candle. Mr. Dibdin says that 'the adjustment of the height of the Methven flame is a matter of too

little certainty, and lends itself to variations of readings in the hands of a biassed or careless operator.' Granting, however, that there may be some slight trouble in properly adjusting the flame, it is not a matter of great difficulty, and the Methven standard is hardly likely to suffer more than any other from careless manipulation. Mr. Dibdin, however, says when dealing with the pentane standard that 'the adjustment of the height of the flame is a matter of certainty.' He also urges that the employment of a chimney (by Mr. Methven) is a serious disadvantage, as the portion of glass exposed to the slot acts as a lens, and therefore affects the results. The objection is, however, hardly fair here, for the width of the strip of glass involved is so very small (¼ in.) that it presents practically a plane surface.

In the standard suggested by Mr. A. Vernon Harcourt, and known as the air-gas or pentane standard, the combustible employed consists of a mixture of air with that portion of American petroleum which, after repeated rectifications, distils at a temperature not exceeding 50° C. This liquid consists almost entirely of pentane, its specific gravity at 15° C. ranging from 0·628 and 0·631.

To prepare the gas, Mr. Harcourt draws into the gasholder the required volume of air, according to the capacity of the holder, and corrected for pressure, temperature, and tension of aqueous vapour; then the corresponding proportion of pentane is poured into the gasholder from a measuring-flask or pipette. The proportion maintained between the air and the pentane is one cubic foot of air to three cubic inches of pentane, measuring the liquid at or near 60° Fahr.; or, measuring both as gases, 20 volumes of air to 7 of pentane.

When the pentane is poured upon the water in the gasholder with about thrice its vapour-volume of air above, it volatilises rapidly and completely. A few minutes are sufficient for the volatilisation of the liquid, but a few hours are required for perfect diffusion.

The opening in the burner has a diameter of a quarter of an inch, and is at the top of a cylindrical tube one inch in diameter and four inches long, the thickness of the disc, forming the mouthpiece at the top of the tube, being half an inch. With a burner

of these dimensions, the mixture of air and pentane gas yields, as nearly as possible, a flame $2\frac{1}{2}$ inches in height when the rate of consumption is 0·5 cubic foot per hour.

The adjustment of the pentane flame to give the unit light (equal to the mean of a long series of tests with standard candles) may be based upon the observations either of its height or of the rate of consumption, and may be effected either by adjusting the height of the flame till the tip of it touches, without passing, a horizontal platinum wire stretched over the burner at the desired height, or by adjusting the rate at which the pentane gas passes through a delicate meter. Experience of the two modes of adjustment has shown that it is both easier and more accurate to trust to the setting of the height of the flame, and to use the rate of consumption as a control only, without taking it into account in reckoning the illuminative value of the gas tested.

No material variation in the light given by the standard flame occurs when, the height of the flame having been adjusted accurately to $2\frac{1}{2}$ inches, the observed rate of consumption does not exceed 0·52 or fall short of 0·48 cubic foot per hour. As a rule, the rate only varies within the narrower limits of 0·51 and 0·49.

A series of experiments performed to ascertain the effect of variations in the proportion of air and pentane, demonstrated that an error or variation of 7 per cent. in the ratio of air to pentane causes a variation of 5 per cent. in the rate at which pentane gas needs to be passed through the meter to maintain a $2\frac{1}{2}$-inch flame, and a difference of only 2 per cent., or ·03 candle, in the illuminative value assigned to the gas tested by comparison with it. But an error of even half this amount is rarely obtained in the actual preparation of pentane gas.

It is remarkable that in only 37 out of 468 testings does the result of one testing differ from the mean result of the set of which it forms a part, by as much as 0·2 candle.

Tests were made with variable height of flame, and the averages of ten observations made at the rate of one a minute, showed that with

Height of flame in inches . .	$2\frac{15}{32}$	$2\frac{1}{2}$	$2\frac{17}{32}$
The corresponding illuminating power was	99·25	100	100·75

Other experiments demonstrated that the illuminating power of the air gas is but little affected by variations in the temperature of the room.

Mr. Dibdin is favourably impressed with the pentane standard, and in a report to the Board of Works he recommended its early adoption. Similarly, the British Association Committee considered it to be reliable and convenient, fulfilling the conditions required in a standard of light, and they likewise urge the rejection of the Parliamentary candle as a standard of light, and the adoption of the pentane standard.

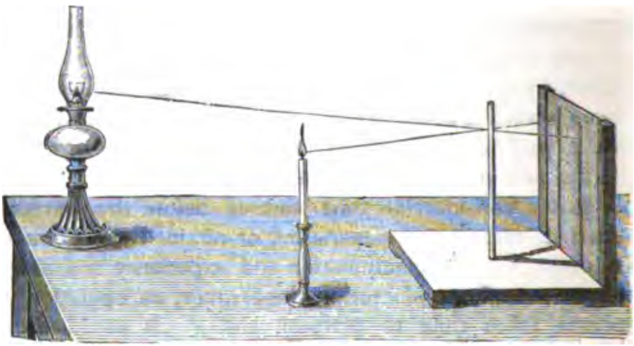
The 'battle of the standards,' as already mentioned, is confined to the types invented by Mr. Methven and Mr. Harcourt respectively. It is probable that the latter is slightly more accurate than the other, but it is less convenient, and is for that reason very rarely adopted in practice, while the Methven screen is very extensively used by gas as well as electrical engineers. The Methven screen is always ready, and measurements can be taken within a very few minutes of lighting the gas. On the other hand, the amount of heat evolved by the pentane flame is so small that a considerable time elapses before the burner has assumed its maximum temperature, or attained the normal rate of burning. Careful manipulation and experience are necessary in the process of manufacturing the pentane, an operation which of course takes time to perform, and which would therefore frequently preclude its use.

Under the circumstances it is perhaps as well that our laws change but slowly, and that the legal substitute for the universally condemned sperm candle has not yet been determined.

Supposing an absolutely reliable and permanent unit of luminosity to be available, we are still confronted by the second difficulty, viz. the want of a means of accurate measurement. Practical photometers are one and all simple comparison instruments, the light emitted by the standard and the source under test being compared simultaneously, and these comparisons must perforce be made by the eye. Unfortunately that organ is untrustworthy as a piece of scientific apparatus and incapable of accurate discrimination. Its sensitiveness also varies considerably with the individual, so that any series of tests should be taken throughout

by the same experimenter, although even then there is some risk of personal error. Of course this difficulty is in some measure overcome by continued practice and attention, but some experiments performed by Professor Schuster illustrate very forcibly the general unreliability of the human eye. He submitted to a considerable number of persons a pure yellow image, and a compound yellow composed of full red and green rays. By means of a 'Nicol prism,' each person could mix the red and green components together in any proportion; and they were asked to make the compound yellow match the simple colour. The result was extraordinary, for whereas one observer required 2·8 times as much

FIG. 320.



red as green to make the match, another took five times as much green as red to produce the same tint.

All practical photometers are based upon the fundamental law that the intensity of illumination on a given surface varies inversely as the square of its distance from the source of light; and upon the fact that the distances of two independent sources of light can be so adjusted that their illumination of the given surface is equal. Then by measuring these distances the relative illuminating powers can be calculated.

The fundamental principle of the Rumford or 'shadow' photometer can perhaps be best illustrated by means of simple familiar apparatus such as that in fig. 320.

It consists of an upright ground-glass screen having fixed

in front of it a small vertical rod. The standard light—in this case a candle—is placed at such a distance as to project a shadow of the rod upon the screen. The lamp, or other source, to be tested, is then brought into position so as to throw a second shadow close to that from the candle, and the exact position of the lamp so adjusted that the intensities of the shadows are as nearly alike as the observer can tell. The distances of the candle and the lamp from the ground-glass screen are then carefully measured, and the comparative luminosities deduced from the law of inverse squares. For example, suppose the distance of the candle to be 12 inches and that of the lamp $3\frac{1}{2}$ feet when the shadows are equal, then the luminosity is $1^2 : 3\frac{1}{2}^2$, that is to say, the light emitted by the lamp is $12\frac{1}{4}$ times as strong as that from the candle, and it may be called a $12\frac{1}{4}$ candle-power lamp. The comparative sensitiveness of the observer can be roughly estimated by moving the lamp to and fro for some distance, when, unless he is a professional photometrist, he will probably find that it is a very easy matter for the personal error to exceed 10 per cent.

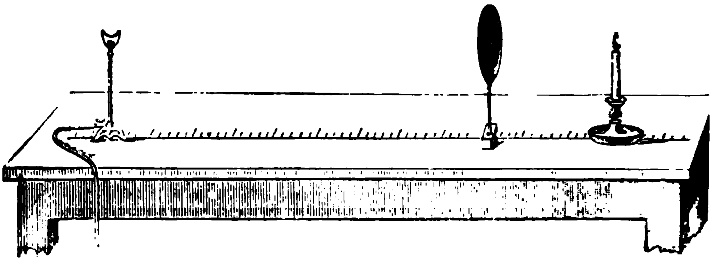
The principle underlying this instrument is simple, for it is evident that the shadow cast by the lamp is illuminated by the candle, while that cast by the candle is illuminated by the lamp, so that, if both shadows are reduced to the same degree of intensity, it can only be due to the effect of equal luminosities upon the surface of the screen derived from the two sources.

The Bunsen or, as it is often called, the 'grease-spot' photometer is, especially for the beginner, an instrument by which more accurate results can be obtained; and it is the one most frequently employed. The principle of the apparatus is shown in fig. 321. A small screen of somewhat opaque paper is stretched on a metallic ring, which is mounted on a stand, movable along a graduated scale. In the earlier forms of this instrument, a semi-transparent grease spot was made in the centre of the disc by means of a little spermaceti dissolved in naphtha, but in the modern practical instrument the whole of the paper, with the exception of a small central patch, is so saturated. To make an efficient screen is a matter of some difficulty, there being a particular thickness of spermaceti which, with each experimenter, gives the best results.

The standard candle is fixed at one end of the scale, and the gas jet or lamp (the luminosity of which is to be measured) at the other end of the scale, which should for convenience be divided into 100, or some other multiple of 10, equal parts. The two illuminants should be placed at such a height that their centres are in a line with the centre of the screen, which can then be moved along the scale until the spot becomes invisible, and the whole of the surface appears to be uniformly lighted; or the screen and standard candle can be fixed, and the lamp under test moved along the scale to the required point.

The bottom of the stand carrying the screen (or lamp) should also be furnished with an index, and, the exact position of this index on the scale being noted, the relative distances of the two illuminants from the screen can be easily ascertained. Their luminosities can then be calculated by squaring these distances. The principle of this instrument is likewise simple. If a single light is held in front of the screen, the greased paper, which allows a portion of the light falling upon it to be transmitted through it, appears, when viewed from that side on which the light is placed, to be darker than the ungreased portion, which reflects liberally the rays falling upon it. If, on the other hand, the light is placed behind the screen, the grease spot or ring appears as a comparatively bright surface upon a dark ground, owing to the fact that the greased paper transmits a large portion of the light falling upon it, while the other part of the screen transmits scarcely any of the rays. When, therefore, the position of the screen between two sources of light is adjusted until the whole of the screen

FIG. 321.



appears to be equally lighted, the two sides will be equally illuminated, the light transmitted by the greased paper being equal to that reflected from the ungreased paper. As a matter of fact, the grease spot is never capable of transmitting the whole of the light falling upon it, neither is the ungreased paper a perfect reflector nor absolutely opaque.

A beam of light falling upon a body is liable to be affected in three different ways: the rays may be transmitted, reflected, or absorbed. Bodies are called transparent when they transmit a large proportion of the rays, but all substances behave more or less as reflectors, for it is only by reflected light that non-luminous bodies become at all visible. All substances also, including even the best reflectors, absorb some of the rays, so that when a reflector is introduced into the measuring apparatus, some difficulty is experienced in estimating the amount of light. Professors Ayrton and Perry designed a photometer especially for electric lighting, at a time when there was a great demand for means to measure the light from an arc lamp. It is based on the 'shadow' principle, but instead of moving the lamp away to a considerable distance in order to compare its light with that of the much feebler standard, a concave lens is employed, having the effect of scattering or dispersing the luminous rays, and projecting only a few of them upon the scale, whence it is known as a 'Dispersion' photometer. As the proportion thus utilised in casting the shadow can be readily determined, depending as it does upon the curvature and absorbing power of the glass, the direct result simply requires to be multiplied by a given constant to determine the relative luminosities. A plane mirror is employed to direct the rays upon the lens, the plane of the mirror being always adjusted to an angle of 45° with the incident beam, so as to avoid the introduction of errors due to varying degrees of absorption for different angles of reflection. The mirror likewise carries a pointer moving over a graduated arc, by means of which the inclination of the incident beam to the horizontal can be indicated.

This instrument is no doubt very useful for laboratory purposes, but it is hardly one that could be placed in the hands of the average operator, for whom the necessary adjustments and

calculations would be too intricate. This does not, however, detract from its value as a piece of scientific apparatus.

Many other forms of photometer have been devised, but they are mostly modifications either of the grease spot or of the shadow photometer, and do not therefore call for further comment.

A beam of light has two other qualities besides that of illuminating a dark surface. It can easily be shown to possess more or less heat rays; also, that if certain compound substances are interposed in its path, chemical decomposition takes place. Were the three portions of the beams—viz. the thermal, the luminous, and the actinic or chemical rays—always united in the same proportions, we should have no difficulty in constructing a photometer accurate in its measurement and independent of the want of sensitiveness in the eye; for we could, on the one hand, use a thermometer, or thermopile and a delicate galvanometer; or, on the other hand, a piece of sensitised paper, such as is used in photography. But unfortunately the proportions vary considerably.

Tyndall ascertained, as the result of a long series of carefully performed experiments, that the luminous rays from several sources of light bear but a small proportion to the obscure or non-luminous rays, the exact proportion of the former being from

An oil flame	3	per cent.
A gas flame	4	„
A white-hot spiral	4·6	„
An electric-arc light	10	„

The arc light appears here as the richest in luminous rays; it is also the richest in actinic rays, but the poorest in thermal rays. The various proportions differ, however, with different carbons, &c. The experiments demonstrate that, if either the thermal or the actinic rays are to be utilised for ascertaining the luminosities of electric lamps, they can only be compared together, or among themselves; they cannot be fairly compared with an oil or a gas flame. It has been estimated that of the solar rays about 34 per cent. are luminous. Some interesting experiments have been made by Professor S. P. Langley and Mr. Very to determine the luminous efficiency of the Cuban fire-fly, and they find

that almost the whole of the rays are luminous. It would be perhaps the greatest single stride of the century if a source of light were produced from which the whole of the rays were luminous, instead of the great majority being of the lower or thermal order.

In the practical measurement of electric lamps, modifications of the Bunsen photometer are, as we have indicated, generally employed. The form most frequently met with is the Letheby, which was designed for gas testing, and which therefore possesses many refinements unnecessary for electric light testing. The Bunsen disc is enclosed in a double conical tube or box to screen off extraneous rays of light, and small angular mirrors are placed opposite a pair of openings in the side of the tube to facilitate simultaneous observations of the two sides of the disc.

The 'Universal' photometer, designed by the late Mr. Hartley, is simple and efficient, and can be used for estimating the luminosities of arc or incandescent lamps in a horizontal or in any other direction. It consists of a long narrow table, with two parallel grooves in the top; sliding in one of these are the Methven screen or other standard and the Bunsen disc, while in the other travels a scale, 21 inches in length, divided into tenths of an inch. For horizontal measurement, the lamp to be tested is fixed on an independent pillar at a known distance from the disc; if the lamp is suspended from the ceiling, an angle measurer is provided to facilitate the estimation of its actual distance.

It is the usual practice for an incandescent lamp to be carefully compared with some standard, such as the Methven screen. It is then in its turn employed as a standard of comparison for other similar lamps, requiring little attention, and affording a ready means of rapidly testing a large number of lamps. It is, however, only employed as a standard for a time, otherwise there would be some risk of error owing to a diminution in the luminosity of the lamp. The method of testing arc lamps is somewhat similar. An incandescent lamp, after being standardised, is in this case also frequently employed as a standard, the arc lamp being placed on a scale at right angles with the photometer bar, which carries a mirror adjusted to an angle of 45° with the luminous beam, so as, in obedience to the law declaring that the angle of

reflection is equal to the angle of incidence, to project the rays upon the greased disc, the quasi-standard being placed so as to illuminate the opposite side of the disc. The comparison is then made by adding the distance between the disc and the mirror to the distance between the mirror and the arc, and regarding this as the distance which has to be compared with that between the disc and the standard. A constant allowance has to be made for the absorption of the mirror, which for a certain angle varies with different samples of glass. It is obviously necessary that the arc should be so screened that none of the rays fall direct upon the disc, and that the angle of the mirror should be kept fixed. With a very powerful arc it would be possible to diminish the percentage of the rays falling upon the disc, by placing the lamp at a greater angle than that of 90° with the scale board or the axis of the disc. A fresh constant would then have to be employed in accordance with the law that the intensity of illumination which is received obliquely is proportional to the cosine of the angle which the luminous rays make with the normal to the surface, allowance being also made for the increased loss due to absorption. Considerable difficulty is, however, experienced in comparing arc and incandescent lamps owing to the greater percentage of blue rays in the former, and it is only after long practice that the comparison can be made with any degree of confidence.

Where the space can be afforded, a photomoter room should be provided, and fitted with opaque blinds, so that all extraneous rays can be excluded. The room, when candles or comparison flames are employed, should be free from draughts and vibration.

In commencing Chapter XV. it was remarked that illumination is the whole object of lighting, and it behoves us now to study, albeit briefly, a few of the points in connection with illumination. By illumination is meant the amount of light falling upon, say, each square foot of the surface to be illuminated, and this amount is of course quite independent of the nature of that surface. The rays which thus fall upon a body may be either reflected, absorbed, or transmitted. No surface reflects all the rays incident upon it, nor is any substance so transparent as to transmit all the rays without loss. Such a substance, could we find one, would be invisible, since bodies which are not themselves illuminants or

sources of light are seen only by reflected light, and those bodies are brightest which reflect the greatest proportion of the rays which fall upon them. Few, if any substances, are truly white, for to be so they must be capable of reflecting rays of every hue equally. Most bodies, however, absorb rays of one colour more readily than those of another, and such bodies are only visible in virtue of the rays which they reflect. A boiled lobster, for instance, reflects red rays readily, but absorbs the blue rays. If, therefore, it were placed in a room lighted from without, and in lighting which all the rays had to pass through windows of cobalt-blue glass (which absorb the red rays), all the rays incident upon the lobster would be absorbed, and it would therefore be almost black or devoid of colour. If a pinch of salt be burned, it will tinge the room with yellow—that is to say, there will be such a preponderance of yellow rays that every object capable of reflecting yellow rays will assume that hue. Although, therefore, we may measure the illumination of a body by the quantity of light falling upon it, we must estimate the visibility or luminosity of such a body by the proportion of the illuminating rays which are reflected from it, and on page 692 we give a table of the reflecting powers of a number of substances. Most objects are viewed by diffused light—that is to say, by rays which have been reflected from surface to surface several times before they reach the eye. The best example of this is sunlight. The solar rays are reflected from roads, houses, &c., into the rooms, and from object to object in those rooms, suffering perhaps hundreds of reflections prior to their impinging upon the retina. It will be manifest that were we dependent upon the direct illumination of objects by the sun, rooms facing due north would be in perennial darkness, while on a cloudy day we should be altogether without light other than that derived from artificial sources.

The illumination of a body depends upon two factors, viz. the quantity of light emitted by the illuminant, and the distance between that illuminant and the body illuminated. The unit of illumination which is more generally accepted is the *candle-foot*, and it is that amount of light falling upon a body at a distance of one foot from a standard candle; as the intensity of light varies inversely as the square of the distance from the source of light,

it follows that were an object placed at a distance of two feet from a standard candle its illumination would be one-quarter of a candle-foot. It has been estimated by Mr. Trotter that the illumination due to the sun on a bright day in the streets of London is equal to thirty candle-feet, while the maximum in the street best lighted by arc lamps is, on the pavement, but little in excess of one-half of a candle-foot. One candle-foot is a convenient illumination for comfortable reading. The number and distribution of incandescent lamps to be employed in lighting any given room or building is a matter of some importance, although the efficiency is frequently governed to a very great extent by local requirements, structural details, and questions of taste. Whatever may be its ultimate destiny the electric light has been up to the present more or less of a luxury, and in the great majority of cases has had to be paid for as such; accordingly, it is essential that the installation engineer, to be successful, should have a certain amount of artistic instinct, and it is to the absence of this that the many hideous fittings and the want of effectiveness so frequently seen in installations are to be attributed. Naturally the man who designs the installation is before all things an engineer, and one whose chief object is to get the greatest amount of light for a given expenditure of energy, so that unless a desire is definitely expressed to the contrary, naked, clear-glass bulbs are almost sure to be used, and frequently so arranged that the intensely brilliant and often dazzling filament directs its rays on to the face of the occupant of the room. For internal domestic lighting no sane man would dream of employing a naked gas flame, and it is not at all exceptional for the globes which are usually employed to absorb 60 or even 75 per cent. of the light emitted, and electric light engineers should reconcile themselves to this, and be content to sacrifice something to comfort and appearance. It is not at all fair to compare an unscreened, incandescent lamp with a shaded gas flame, and say that the 16 candle-power incandescent lamp gives out two, three, or four times as much light as the gas flame. Nevertheless, this manifestly objectionable comparison is frequently made. As the intensity of illumination varies inversely as the square of the distance from the illuminant, it will often become a serious question whether it is preferable to place unscreened lamps

with reflecting shades high up, or to place screened lamps, or lamps with 'frosted' bulbs, low down. Or again, more especially in small rooms, a more uniform distribution of light will be obtained from four 8 candle-power lamps than from two of 16 candle-power, although the prime cost for wiring and fittings will be heavier. An obscured or frosted globe, although it absorbs more of the rays than does a clear globe, gives a better effect, and as the pupil of the eye contracts when looking at the comparatively dazzling light of the unscreened filament, it is possible that the number of rays which actually enter the eye will differ but little in the two cases. The filament in a frosted lamp is invisible, and the comparatively large bulb looks very much as though it is in reality the source of light, and the luminous area being thus enlarged the luminous intensity is reduced, and the contrast between the source of light and the lighted objects is less striking. With an ordinary unscreened gas flame a room looks very poorly lighted in comparison with the effect produced by placing a globe over the burner, although we know as a matter of fact that there is less light emitted in the latter case than in the former. Moreover, the distribution from a lamp with a ground-glass bulb is very different from that obtained with a clear one. We may, in fact, look upon a sheet of ground glass as being composed of an almost infinite number of small and irregular prisms. Rays from every point of the filament impinge upon every portion of the glass, and then passing through different thicknesses of the bulb they undergo refraction to such an extent that practically each little prism becomes a separate and distinct source of light, its rays passing out in every conceivable direction. Of course if the lamp is actually out of the range of the eye, clear globes should be used, so that the objects in the room, which have no contracting pupil and which are seen only by reflected light, may receive the maximum number of rays.

It does not always follow that anything approaching very closely to uniformity in illumination is required for internal work. For example, in an office the light is wanted over the tables or desks, and not on the floor between them; in dining-rooms the light is required over the tables rather than on the walls. Where uniform illumination is required in a room with fairly light walls,

and with lamps seven and a half or eight feet above the floor, a good rough rule is to allow from three quarters to one watt per square foot of floor space. With lamps of good average efficiency the smaller value is sufficient for comfortable reading. On the 1 watt basis a room would require a 16 c.p. lamp for every sixty square feet of floor space—assuming, that is, that this lamp takes 60 watts. A great deal, however, depends upon the colour and surface of the surroundings. Dull and dark surfaces absorb a very large proportion of the luminous rays which impinge upon them and convert them into heat, while light and smooth surfaces reflect them freely, and by repeated reflections add considerably to the illumination of the room. Dr. Sumpner has published the following table, showing the reflecting powers of a number of substances with which he experimented.

Table of Reflecting Powers

	Per cent.		Per cent.
White blotting paper	82	Deep chocolate-coloured paper	4
White cartridge paper	80	Plain deal (clean)	40 to 50
Tracing cloth	35	,, (dirty)	20
Tracing paper	22	Yellow cardboard	30
Ordinary foolscap	70	Parchment (one thickness)	2[illegible]
Newspapers	50 to 70	,, (two thicknesses)	3[illegible]
Tissue paper (one thickness)	40	Yellow painted wall (dirty)	20
,, ,, (two thicknesses)	55	,, ,, (clean)	4[illegible]
Yellow wall paper	40	Black cloth	1[illegible]
Blue paper	25	Black velvet	0[illegible]
Dark brown paper	13		

It thus appears, says Dr. Sumpner, that even a dull-looking wall will reflect as much as 20 per cent. of the light incident upon it. A wall of ordinary tint reflects from 40 to 50 per cent., while a good white surface reflects over 80 per cent. A clean white-washed ceiling reflects as much light as an ordinary mirror, for although extremely good mirrors may be obtained which will reflect as much as 90 per cent. of the light incident upon them measurements made with common mirrors do not show a greater reflecting power than 82 per cent. A room with its surfaces well whitewashed thus needs only one-fifth of the candle-power

produce any given amount of illumination that it would need if its walls, ceiling, &c., were all painted black.

The student will not, therefore, be surprised to learn that it is no unusual experience to find that while one room may be uniformly well lighted with an expenditure of three-quarters of a watt per square foot, another room will be but dimly lighted with an expenditure of $1\frac{1}{2}$ or even 2 watts.

CHAPTER XVII.

INSTALLATION EQUIPMENT, FITTINGS, ETC.

ONE of the most important details to be considered in connection with an electric light plant is the means to be adopted for transferring the energy from the generator to the lamp. In telegraphy it is a matter of secondary importance whether the line connecting the sending and the receiving stations measures, say, 2,000 or 2,500 ohms in resistance, the number of primary cells employed for working the wire being simply varied according to this resistance. Consequently, unless a high-speed system of working is to be adopted, good iron wire answers every purpose, for it is a fairly good conductor, it is mechanically strong, and it is cheap. For high-speed working, copper is resorted to because the electro-magnetic inertia of iron is too great to permit the necessary rapidity of current alternation.

In electric lighting, copper is always employed for the conductor. The current to be carried is usually very strong or heavy, and it is imperative that the loss of energy due to the resistance of the conductor should be brought down to the lowest practicable limit. Were iron to be employed, it would be necessary to give it six times the sectional area of the copper to obtain the same conductivity, and an iron wire or rod of such dimensions as it would be frequently necessary to employ, would be too rigid for handling and bending. It would be necessary to make it in definite lengths and then to connect these lengths together at the place where they are to be used. But such a rod would also present very many additional difficulties in the way of insulation, and add considerably to the cost of that portion of the work. In fact, an insulated iron conductor would be considerably more expensive than one of copper offering the same resistance. The

recently extended use of rapidly alternating currents is another reason against the employment of iron conductors.

It will be seen, from a study of the table given on p. 22, that the choice of materials for electrical conductors of any kind is really limited to the two metals above mentioned, viz. copper and iron; so that for electric lighting work we have no alternative but to use copper.

The accompanying table concerning the various sizes of copper wire generally employed gives some instructive details. It will be seen that most of these conductors are made up of a number of comparatively small wires stranded together, the chief objects being to impart greater flexibility and to reduce the risk of complete fracture.

Now, as in overcoming the resistance of a conductor electrical power is wasted, and as it costs money to develop electrical power, it is evident that in any commercial system such waste must be kept down to a minimum. This can be done by simply reducing the resistance, that is, by increasing the size of the conducting wires; but as this also is an expensive matter, care must be taken that the addition thus made to the expenditure in conductors is not so excessive as to more than counterbalance the cost of the power continually being saved. It has been laid down as a general rule, that, for the transmission of any given current, the size of the conductor most economical to employ is one offering such a resistance that the cost of the energy wasted per annum in heating the conductors should be equal to the interest per annum on the original outlay upon them. Knowing the average current to be transmitted, it becomes easy to find the average electrical horse-power wasted in a conductor of any given resistance; but the cost of developing a horse-power depends upon many conditions, principally local, such as the cost of fuel, attendance, rental, repairs, prime cost and efficiency of the plant. And with regard to the conductors themselves, it must be remembered that it is not merely a question of the quantity and price of the copper employed, but also of the insulation and laying.

Most main conductors are, in England, placed underground, and in many cases the cost of laying considerably exceeds the

actual cost of the wire. Further, although the resistance of a wire one inch in diameter is only one-fourth of that of a wire half a

Number of wires in strand	Standard gauge of each wire	Diameter (in inches)		Equivalent to solid wire		Weight of Conductor per statute mile (lbs.)	Resistance at 60° Fah. per mile (ohms)
		Of each single wire	Of the strand	Diameter (inches)	Area (square inches)		
1	22	·028	—	·028	·0006	12	72·52
1	21	·032	—	·032	·0008	16	55·53
1	20	·036	—	·036	·0010	21	43·87
1	19	·040	—	·040	·0012	26	35·53
1	18	·048	—	·048	·0018	37	24·68
1	17	·056	—	·056	·0024	50	18·13
1	16	·064	—	·064	·0032	65	13·88
1	15	·072	—	·072	·0040	83	10·97
1	14	·080	—	·080	·0050	102	8·884
1	13	·092	—	·092	·0066	135	6·718
1	12	·104	—	·104	·0085	173	5·257
1	11	·116	—	·116	·0105	215	4·225
1	10	·128	—	·128	·0128	262	3·470
1	9	·144	—	·144	·0162	332	2·742
1	8	·160	—	·160	·0201	409	2·221
3	25	·020	·042	·034	·0009	19	46·79
3	23	·024	·051	·042	·0014	28	32·50
3	22	·028	·059	·049	·0019	38	23·87
7	25	·020	·060	·053	·0022	45	20·01
7	23	·024	·072	·064	·0032	65	13·89
7	22	·028	·084	·075	·0044	89	10·20
7	21½	·030	·090	·080	·0050	102	8·893
7	20½	·033	·099	·088	·0061	124	7·342
7	20	·036	·108	·096	·0072	147	6·175
7	19	·040	·120	·107	·0089	182	5·002
7	18	·048	·144	·128	·0128	262	3·473
7	17	·056	·168	·149	·0174	356	2·552
7	16	·064	·192	·171	·0229	465	1·953
7	15	·072	·216	·192	·0289	589	1·543
7	14	·080	·240	·213	·0356	727	1·253
19	20	·036	·180	·159	·0198	402	2·261
19	19	·040	·200	·176	·0243	496	1·831
19	18	·048	·240	·211	·0349	715	1·271
19	17	·056	·280	·247	·0479	973	·9300
19	16	·064	·320	·282	·0624	1,270	·715[illegible]
19	15	·072	·360	·317	·0789	1,608	·56[illegible]
19	14	·080	·400	·352	·0973	1,985	·45[illegible]
19	13	·092	·460	·404	·1282	2,625	·3402
19	12	·104	·520	·458	·1647	3,354	·270[illegible]
37	16	·064	·448	·394	·1219	2,482	·36[illegible]
37	15	·072	·504	·443	·1541	3,142	·28[illegible]
37	14	·080	·560	·493	·1909	3,879	·2343
37	13	·092	·644	·566	·2516	5,130	·1772
37	12	·104	·728	·640	·3217	6,555	·138[illegible]
61	13	·092	·828	·728	·4162	8,477	·1072
61	12	·104	·936	·823	·5319	10,832	·03[illegible]

inch in diameter, it does not cost anything like four times as much, nor even twice as much, to lay the thicker wire as it does to lay the thinner, for the labour of removing and replacing the paving, earth, &c., would be almost the same in both cases. Again, the insulation of the wire is an important and expensive item, which does not increase so rapidly as the resistance of a wire is reduced by an increase in its size; so that it does not by any means follow that a given reduction in resistance entails a proportionate increase in expense, and it becomes impossible to lay down any hard and fast rule which shall determine the exact size of conductor for any given case.

It may be noticed incidentally, that when the diameter of a round conductor is doubled, although its sectional area and therefore its conductivity is increased fourfold, its surface is only doubled. Therefore, if a current of four times the strength is passed through it, the heat developed will be four times as great (since power wasted $= C^2R$), while the surface at which radiation takes place has only been doubled. The temperature of the thicker wire will consequently rise higher than that of the thinner one, when they carry currents in proportion to their conductivities. A wire employed for the purpose of transmitting current to lamps or motors should never be so small that the maximum current transmitted can appreciably raise its temperature; but for other special cases it may be noted that one advantage attending the use of bare conductors is the greater facility afforded by them for the radiation of heat as compared with covered conductors.

So many considerations, mostly special for every particular case, enter into the question of the best size and shape of the conductor consistent with strict economy, that we cannot discuss the matter fully here. But with regard to the reduction of resistance by the employment of high conductivity copper, it should be noticed that, as the presence of a minute quantity of foreign matter causes such a great increase in the resistance of this metal, it is *always* economical to use the purest copper obtainable commercially.

In systems of distribution of electrical power by means of a constant current, the question is comparatively simple, as the

current employed is not a heavy one, and has the same value at all times and in all parts of the circuit. The chief difficulty likely to arise is in providing for future extensions of the system when the potential difference which can be applied at the ends of the circuit is limited.

The more interesting and more difficult problem consists in the supply of current to lamps, or other apparatus, at a constant potential; for then the main conductors have to carry a very heavy and variable current. The matter becomes more difficult if the lamps are distributed over a wide area, or are situated at a distance from the generating station. As has been pointed out in Chap. XIII., the power wasted may in such cases be reduced to a minimum, by transmitting it in the form of a small current at high pressure, and reducing the pressure at the required point, to a suitable value. But such a system has its disadvantages. Although the cost of the copper is greatly reduced, the high potential difference employed demands very efficient and expensive insulation, the engines and dynamos must always be kept running, and when very little power is being demanded the efficiency of the transformers and of the whole system falls to a low value. For even when the secondary circuit of a parallel transformer is disconnected, some current passes through the primary, and when only one or two lamps are joined up, the power appearing in the secondary may be but a comparatively small fraction of that absorbed by the primary. When the number of transformers is large, the total power wasted becomes considerable during the times when little or no light is required.

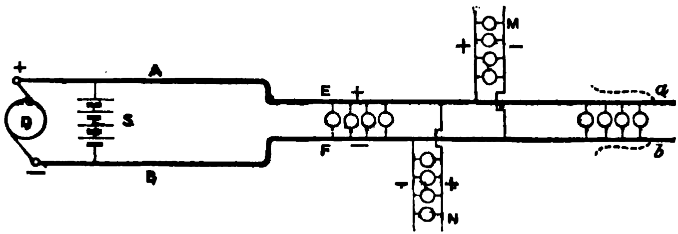
In the other method of distribution by means of continuous currents direct from the dynamo to a number of lamps all joined up in parallel, the chief problems to be faced are the heavy loss occurring in the mains and the difficulty of regulating the supply to each lamp.

Such an arrangement is indicated by the diagram in fig. 322, where D represents a dynamo capable of maintaining a constant potential difference at its terminals; A and B, the main leads from the machine to the nearest lamp; and E, F the continuation of those leads, between which the lamps are placed. Suppose there to be 100 lamps so joined in parallel, each requiring a current

of half an ampere, and a potential difference at its extremities of 110 volts. The total current supplied by the dynamo with all the lamps in use would be 50 amperes, and this current would have to be carried by the main leads A and B. Supposing the resistance of A and B to be one-tenth of an ohm, the power wasted in overcoming this resistance would be 250 watts, and the consequent fall of potential 5 volts. Therefore the machine must develop at least 115 volts at its terminals in order to maintain 110 volts at the *nearest* lamp.

Now a further fall of potential would take place along the more distant mains, E, F; suppose this to amount to 10 volts, then the pressure at the most distant lamp would only be 100 volts, while if this were raised to the desired value of 110 volts by

FIG. 322.



an increase at the dynamo, the nearest lamp would then be working at 120 volts, or 10 volts above its proper pressure. Even ignoring the waste of power, such a difference could not be permitted if similar lamps were used throughout the system, as some would be giving far above and others far below their normal candle-power.

It would, however, be practicable, but very inconvenient, to employ different types of lamp, placing those made to run at 110 volts at the end near the dynamo, and others constructed for 100 volts at the further end of the line, and so on. But even then, if the dynamo were perfectly regulating—that is to say, capable of maintaining a constant potential difference at the brushes under all circumstances—the potential at the far end of the mains would rise considerably when any number of the nearer or intermediate lamps were cut out of circuit.

Referring again to the figure, it will be observed that the mains at any one point only carry a current equal to that required by all the lamps beyond that point. Thus, while the portions, A, B, take the whole current, those portions between the last lamp and the last but one carry only half an ampere. The size of the mains might, therefore, be reduced by one hundredth as every lamp is passed, and the same density of current in the conductor be retained. This is equivalent to bunching 100 wires together to form the main, and taking out one of them at every lamp. If the 100 wires were separately insulated—that is to say, if a separate lead and return wire were used between the machine terminals and each lamp—the pressure at the ends of these leads would be constant; and since the resistance in each independent lamp circuit is also constant, the pressure at each lamp would be unaltered by any variation in the number thrown in circuit. This forms a means of maintaining a perfect regulation, although of course the actual pressure at the lamp would depend upon the resistance of its particular leads. Great as are the advantages of such a method, the expense would forbid its being employed in an installation extending over a large area. It will be seen, however, that with ordinary mains, if the resistance is sufficiently low to make the fall of potential very small, then the variation which would take place in the potential difference at the extreme ends of the circuit becomes negligibly small. An extreme variation of 2 volts might be allowed, and then, by maintaining the normal pressure of 110 volts near the middle of the system, the nearest lamp would have but 111 volts and the furthest 109.

It is necessary to be able to observe in the engine-room the pressure existing at the far and near ends of the mains at any moment, so as to be able to keep one point as much below as the other is above the normal pressure; and this can be done by leading 'pilot-wires' from the mains at those points to a voltmeter placed at the generating station.

For instance, in fig. 322, a thin wire might be led from the point *a* and another from *b*, each to one terminal of the voltmeter, which would afford an indication of every variation at the extreme end of the mains. A second pair of pilot-wires might be led from the nearest lamp; or by leading one pair only, connected

to the mains at the centre of the system, and keeping the potential there at 110 volts, a good average regulation might be maintained.

At an installation at Kensington Court, several thousand 100-volt lamps are run in parallel, batteries of secondary cells being used in conjunction with the dynamos, for regulating, and assisting the machines to meet any large demand. Several circuits branch out from the engine-house, some of the lamps being 900 yards distant. At the extreme ends of all the mains, a pressure of 100 volts is maintained, while that at the nearest lamp does not exceed 102 volts. A pair of thin wires is led, as mentioned above, from the end of the mains, to a voltmeter in the engine-house, and when this instrument indicates a fall of potential (caused by the switching in of more lamps) the attendant immediately switches one or two secondary cells on to that pair of mains, in series with the existing cells, thus raising the pressure to the required value; the cells being of course cut out when the voltmeter indicates a rise of potential. The mains employed in this case consist partly of ordinary insulated cable, and partly of bare copper conductors stretched over porcelain insulators, in concreted channels.

Although on a simple parallel system of distribution, the arrangement is such that the whole of the lamps are connected in parallel between the two mains, it is evidently impracticable to join them directly across (as indicated in the case of the nearest and furthest lamps in fig. 322), when the mains are carried under the roadway. It is necessary to lead a wire from each main to every group of lamps, say to every house supplied, in the manner indicated at M, N. The higher potential mains are throughout marked +, and the lower potential, or return wires, −. These subsidiary mains should be proportioned in size according to the number of lamps to be supplied by them.

It is not practicable, however, to sufficiently reduce the resistance of a single pair of mains leading direct from the dynamo to maintain even approximately a constant pressure at all the lamps if they are distributed over a large area; a method of facilitating regulation in such a case, by the employment of subsidiary mains which feed the mains proper at certain points, but are not themselves tapped by lamp-circuits, will be described later on.

The method of employing a battery of secondary cells so as to

assist in the regulation, or in the maintenance of a constant potential, is indicated in fig. 322, where S represents such a battery. The cells are joined in parallel with the dynamo, and are charged by it without any alteration in the connections being necessitated.

The interactions between the two generators—the dynamo and the battery—may be embraced under three heads. (*a*) When the E.M.F. of the battery is less than the potential difference at the dynamo terminals, the machine is supplying current to the lamps and at the same time charging the cells, the strength of the current passing through the cells depending upon the excess of the potential difference maintained by the machine over the E.M.F. of the cells. (*b*) When the E.M.F. of the cells becomes equal to the potential difference at the machine terminals, both generators are equally active in feeding the lamp circuit. (*c*) When the E.M.F. of the cells rises above the normal—that is, above that potential difference which is required to be maintained at the terminals of the generators in order to maintain the right pressure at the lamps—then the battery not only feeds the lamp-circuit, but raises the pressure at the machine terminals. This rarely happens, but, the machine being shunt-wound, the effect is to increase the current through the field coils, giving a stronger field, which again tends to increase the E.M.F. developed. When the potential difference thus rises, it becomes necessary to cut out one or two cells to prevent the pressure rising sufficiently high to injure the lamps. A suitable switch (such as that illustrated in fig. 275) is employed for this purpose, and the regulation effected by an attendant in accordance with the indications of the voltmeter.

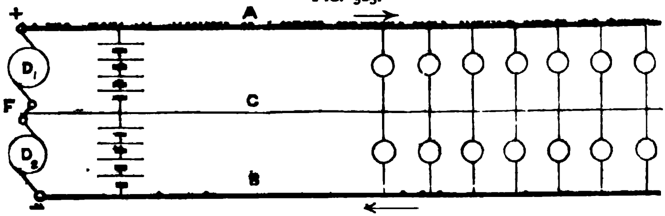
It will be remembered that if the engine should break down, the cells would drive the shunt machine as a motor in the same direction; but an automatic cut-out should be provided to cut off the dynamo when the back-current from the cells exceeds a certain limit. A piece of apparatus capable of performing these operations was described in Chap. XIV.; it disconnects the machine when from any cause its potential difference falls materially below the E.M.F. of the cells. Under such circumstances the cells would be called upon, and should be able, to run even the whole of the lamps for a short period, or a portion of them for a considerable time.

It also becomes possible to economise power and the expense of attendance, by only running the machine during the hours when the demand is a maximum, allowing the cells to supply current to the few lamps required at other times.

It may occur to the student that a considerable saving in the mains would be effected by joining groups of lamps in series, between the mains, all the groups being thus placed in parallel. This is so; for if the lamps were placed in sets of four in series, the potential difference between the mains would be four times that at the ends of one lamp, say 400 volts instead of 100. By this means the maximum current in the mains would be reduced to one-fourth, and the weight of copper correspondingly reduced, to give the same rate of loss of power.

But some serious difficulties arise in connection with such a system; for instance, if the filament of one lamp in a set breaks,

FIG. 323.



the other three lamps in that set are immediately extinguished; and if, to remedy this, the faulty lamp is merely short-circuited, the remaining three get too much current, and may also be damaged. Of course a device may be adopted to automatically switch in a second lamp, or to replace the broken one by a resistance equal to it; but the latter arrangement is undesirable on account of the waste of power; and in either case the extra fittings cause additional trouble and expense.

The same objection arises in the ordinary case of switching out one of a batch of lamps.

But even if the lamps are joined in sets of only two in series, a considerable saving is effected; and a method by which this can be done, without introducing any of the difficulties referred to, is indicated by the diagram in fig. 323. It is known as the 'three-wire system.'

Two equal dynamos, D_1, D_2, are joined in series, and connected to the mains, A, B, in the ordinary manner. That is to say, the positive terminal of D_1 is joined to the positive main, A, and the negative terminal of D_2 to the main B, while the negative terminal of D_1 is coupled to the positive of D_2. Suppose each machine to be capable of maintaining a potential difference of 110 volts; then when they are so joined in series they maintain the mains A and B at a difference of 220 volts. The lamps being joined, two in series, across the mains as indicated, the potential difference at the extremities of one of them is 110 volts. A third wire, C, much smaller than the mains, connects the junctions of the pairs of lamps, and is also joined to the junction of the dynamos.

Now when the number of lamps between A and C is the same as the number between B and C, the potential is the same at every point along the wire, C. Hence there is no tendency for any current to flow along the centre wire; it might, in fact, be cut at any point, or removed altogether, without in any way affecting the working of the system. But when the lamps on either side of it are made unequal in number, this state of balance no longer exists. Suppose a lamp between A and C to be switched out of circuit; then the resistance between A and C is greater, and therefore the fall of potential becomes greater, than between B and C. But the mains A and B are kept at approximately the same potential difference, and if the difference between A and C is increased, it can only be by the lowering of the potential of C. The effect of cutting out a lamp between A and C, then, will be to lower the potential of C near the point where the lamp is disconnected. But the potential at the point F remains unaltered; consequently this difference of potential establishes a current along the wire C, from the junction of the machines to the lamps. The strength is equal to that which flows through one lamp circuit; it may, in fact, be considered as the current which passes through the additional lamp between B and C. If a lamp between B and C is now switched out, balance is again restored, and no current passes along C. When the number between A and C is made the greater, the difference between those leads is lessened—that is, the potential of C near the lamps is raised. This determines the flow

of a current *from* the lamps to the junction of the machines along the centre wire. If the whole of one set of lamps were cut out, then the centre wire would have to carry the current supplied to all the lamps in the remaining set, in which case it would require to be as large as the other mains; in some cases the three mains are made equal, but it is usually possible to arrange the lamps so that this extreme case would never happen. Under favourable conditions the current which the centre wire has to carry, due to the difference in the number of lamps on either side of it, may be made comparatively small; and, consequently, the wire itself can be made much smaller than the mains proper.

It has been proposed to provide each lamp with a switch, by means of which it may be joined up between the centre wire and either main; the brighter light would be obtained from the main which already had the smaller number of lamps joined to it, and, consequently, the consumers, in their anxiety to obtain the best light, would assist in the regulation of the system. The objection to such an arrangement is that, although it effects a saving in that it enables the middle main to be made smaller, it necessitates three wires instead of two being led to every lamp switch, as well as involving a slightly more expensive type of switch.

Secondary cells may be employed in conjunction with the machines, as indicated in the diagram; two complete sets of cells are needed, their positive and negative terminals being connected to the mains and to the centre wire in the same manner as are the dynamo terminals. The principle may be extended to a four- or even a five-wire system, but such methods of distribution should only be adopted when the area to be lighted is sufficiently extensive to enable the saving effected in the cost of the mains, to more than balance the disadvantages due to the increase in the cost of the plant and to the additional complications.

A means of reducing the difficulty of maintaining a uniform potential difference along lengthy mains is afforded by the use of independent conductors connecting various points in the circuit direct with the generating station, and these subsidiary leads are termed 'feeders.' In some cases the mains themselves are not connected direct with the generator, the whole of the current being supplied to them at suitable points by way of the feeders.

When the potential difference at or near the particular poin which a pair of feeders is connected varies (as it does, wit change in the number of lamps in use), this difference is c pensated for by correspondingly varying the pressure applie the feeders, or by some other means varying the current pass through them. When, for instance, the number of lamps circuit is increased, the pressure between the mains falls, more current is required to be supplied by the feeders, and *versâ*.

It becomes necessary, therefore, to provide some means promptly indicating, at the generating station, the variations of potential difference at the points where the feeders join the ma This is readily supplied by the employment of pilot wires, the manner already described, these wires being simply conne to a voltmeter. When the instrument shows a fall of potenti the vicinity of the point at which a particular pair of feeders the mains, the electrical pressure along that pair of feeders augmented until the distant point is raised to the requ standard. On the other hand, should the potential differenc the mains rise, then that on the feeders must be reduced. economical adjustment in this way is somewhat difficult of att ment. It would, for example, be hardly practicable to use separate dynamo for each pair of feeders, and to continually v its output to suit the demand. It is preferable to use one or m dynamos connected to a pair of 'omnibus' bars, from which whole of the feeders radiate. The potential difference bet these bars must be kept equal to the maximum required, and regulation can then be effected by inserting resistance or coun electro-motive force in the respective feeder circuits.

The insertion of resistance coils, however, while it is effec and convenient, is wasteful. A more economical plan is to in duce a few secondary cells in each feeder, in such a manner they oppose the feeding current. The effect is simply to op a counter E.M.F. to the dynamo (since the cells have practicall resistance), but the potential difference is varied by the rather steps of two volts at a time. In making any change both fee must be similarly treated.

With the three-wire system it is obviously necessary to

three feeding mains to each point and to connect pilot wires therefrom to two separate voltmeters.

The advantage of using several comparatively small machines joined in parallel, to supply the omnibus bars, is that a dynamo may be switched out and stopped when the demand for current falls.

When the feeders vary considerably in length, it may be advisable to divide them into two or even more groups according to their resistances, and supply the longer ones from a pair of bars maintained at a proportionately higher pressure than the similar bars supplying the shorter feeders.

Turning now to the methods of supporting, protecting, and insulating the conductors, we immediately observe that they naturally divide themselves into two classes—viz. overhead and underground.

The overhead system has the advantage of cheapness in construction, and it affords great facilities for inspection and repair, and for subsequent extensions. It is, therefore, generally employed where the local conditions are favourable, where the current employed is not so heavy as to require a very massive conductor, and where the potential difference is not excessively high. The system has, however, the disadvantage that the insulation is liable to considerable variation with weather changes. This can to a great extent be prevented by good construction, and the employment of properly designed 'insulators.' A series circuit, such as is used for arc lamps or low-resistance incandescent lamps, lends itself readily to the employment of overhead mains, since the current is in such cases constant, and rarely exceeds ten amperes. A very small wire would be sufficient to carry such a current, but its size is really determined more by mechanical than electrical necessities. For example, a wire of No. 12 S.W.G. would carry the current with safety, but a No. 8 is practically used on account of its greater strength. When the conductor is stranded, 7 No. 16's are employed, although 7 No. 20's might, from an electrical point of view, suffice. We ought perhaps to mention that all overhead bare conductors must be of hard-drawn copper in order to obtain the requisite mechanical strength. Ordinary pure copper is comparatively soft, and in a span of any considerable length cannot sustain its own weight; while in a gale, the wind pressure

enormously increases the strain upon the wire. It is now poss to obtain pure copper wire having a breaking weight of from 30 tons per square inch; the high tenacity is obtained sole the molecular arrangement given to the particles during the proc of drawing, and if the copper is really pure the increase in re- tance due to the hardening should barely exceed two per cent.

Bare conductors are supported on insulators which are in t supported by poles either of iron or wood according to lo circumstances. One advantage pertaining to wood is that in event of an insulator breaking the conductor is still partially sulated from the earth, which would not be the case were an pole employed. Iron poles are obligatory for over-house work where appearance has to be taken into account. The best wo pole is that which consists of the complete trunk of a straight fir or other similar tree, which, after having been well seasone thoroughly impregnated with good creosote. The natural life of pole is enormously lengthened by this treatment.

Insulators can be made from a variety of substances, but climatic and other cogent reasons, white glazed porcelain is m frequently employed.

The chief requirements are hardness, smoothness, and imp viousness to moisture. Lacking either of these, the insulator practically useless. It should be hard in order to resist abra by the wire; it should be smooth, to prevent the accumulation dust and dirt, to facilitate cleansing by rain, and to avoid the necessary wearing away of the conductor; and it should impervious to moisture, in order that the rain should fall instead of entering the pores of the substance and reduce, m or less permanently, its insulating properties.

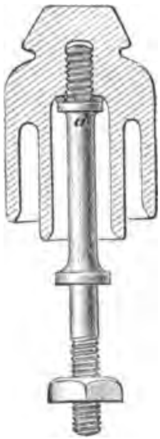
Brown earthenware, especially if well made from a suitable c is also a good material. It is very hard, very durable, has a h resistance, and the glaze which it can take, although it is no good and perfect as that on porcelain, is tolerably smooth, and allows the rain, unless the fall is very heavy, to gather in dr instead of forming a continuous film, as ebonite would Although porcelain offers a higher resistance than brown earth ware, the material varies very considerably, both in its constitut and in its manufacture. Some kinds are almost spongy, and

the glaze covers them there is no possible means of testing, except by breaking them. The glaze often cracks after a few months, and then, if the interior is at all porous, it absorbs moisture, and so in time loses its insulating properties. When perfect, it is undoubtedly the best insulator available.

It must further be pointed out that the insulator should be sufficiently strong to withstand the maximum stress likely to be imposed upon it by the wire. When all is quiet the insulator has simply to bear the weight of half the span of wire on either side of it, but when there is much wind the strain is increased considerably by the swaying of the wire.

In the case of a sound insulator, practically all the leakage takes place over the surface; and in order to make the path taken by the leakage current as difficult as possible, it is necessary to so design the insulator that it shall have the maximum length, with the minimum area of surface between the wire and the steel pin or bolt supporting it.

FIG. 324.



Considering the fact that the E.M.F. in an electric-lighting circuit is comparatively high, it is pre-eminently essential that the insulation should be of the best; parsimony in this respect is very likely to prove but the forerunner of disaster. When the line is straight, so that normally there is no lateral strain, and the conductor is less than a quarter of an inch thick, the porcelain insulator illustrated in fig. 324 is suitable. It consists of a double 'cup' manufactured in one piece; the inner cup is shielded from rain by the outer one, and the length of the surface between the conductor and the supporting bolt is considerable. The peculiarity about it is that it is provided with an open coarse screw thread by means of which it is screwed on to the bolt, which in its turn is permanently fixed to the arm or bracket on the pole. An india-rubber washer, placed above the shoulder *a* at the bottom of the thread on the bolt, allows the insulator to be screwed on tight without involving a risk of splitting it or stripping its thread. The principal advantage pertaining to the use of a screw bolt is that, in

the event of fracture, the insulator itself can be replaced without necessitating the removal of the bolt. One method of fixing the wire to an insulator is illustrated in fig. 325. The conductor is laid in the groove, and a piece of thin binding wire, three or four feet long, is twisted several times round the conductor on one side, A, of the insulator; it is then wound round the insulator and is next twisted several times round the conductor on the other side, B, after which it is wound back again, round the insulator once more, and again over the conductor on the side A. Hard wire is not suitable for binding wire, as its springiness prevents its remaining exactly in the position in which it is placed, tight against the main wire. Sometimes the bindings are soldered.

FIG. 325.

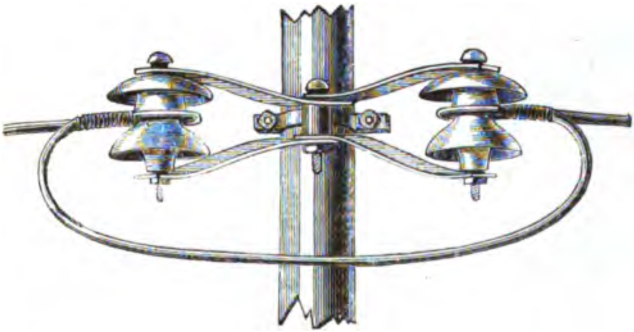
FIG. 326.

When high potential differences are employed, no trouble or expense should be spared to ensure the most thorough insulation possible. A form of insulator very largely employed for this purpose, especially in humid districts, where the risk of leakage is great, is illustrated in fig. 326. It is known as the 'fluid' insulator, from the fact that a quantity of oil is interposed in the path of leakage; the lip of the porcelain cup is bent up on the inner

side to form a circular channel, in which the oil is placed by means of a small syphon capable of holding the required quantity. Experience has shown that very little dust accumulates in the channel, while the formation of a continuous film of moisture between the iron bolt and the conductor is entirely prevented.

These insulators, which are usually cemented to the bolt, are made in a great variety of shapes. In one case there is a separate oil cup supported on a pin which passes through the bolt; this cup is placed below the insulator proper, and the lower edge of the inner cup of the latter is immersed in the oil. When necessary the pin can be removed, and the cup allowed to slide down the bolt, for the purpose of cleaning and

FIG. 327.

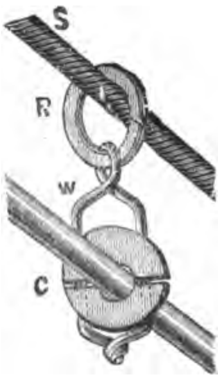


refilling with oil; the cup can easily be placed in position again, and the syphon is therefore dispensed with.

In fig. 327 is illustrated a form of insulator, known as the double shackle, which is useful on heavy lines. It consists of two insulators of porcelain of the shape shown; each has a stout iron bolt passing through it, and is supported by a pair of iron straps bolted to the pole, which, in the case illustrated, is of iron. The main wire is looped round the neck of each insulator, and fixed by a small binding wire wrapped on tightly. The straps of each insulator being independent of those supporting its neighbour, freedom of motion through a large angle is permitted, thus allowing a direct pull to be obtained. The shackle should be employed in all cases where the wire makes an angle at the pole.

When an insulated aërial conductor is used, it cannot be attached to the insulators direct, because the friction which is always at work would speedily cause the abrasion of the insulating material, and that at the very point where complete insulation is sought—viz. at the insulator itself. There is also the further difficulty that an ordinary covered cable has not sufficient tensile strength to enable it to support its own weight in a span of any considerable length. In such cases, a steel wire or rope S (fig. 328) is supported by shackle insulators, and carries a number of split steel rings, R. Engaging in each ring is a galvanised iron wire loop W, which supports a vulcanite chair C, and through which the cable is passed.

FIG. 328.



Sometimes the conductor is suspended midway between a pair of steel ropes by means of V-shaped pieces of iron wire, each piece being attached to three small reels of white porcelain threaded one on to the conductor and the others on the ropes.

One of the most important details in connection with the running of electrical conductors is that of jointing. The chief features which should pertain to a well-made joint are, that the electrical continuity should be fully maintained, that its mechanical strength should be at least equal to that of the conductor itself, that no free ends should be left on the finished joint, that it should be durable both electrically and mechanically, that it should be as compact as possible, and that with a covered wire the insulating coating should be made continuous and as uniform as possible.

For bare solid conductors up to a quarter of an inch or so in diameter, there is no better joint than that known as the 'Britannia.' Fig. 329 illustrates a joint of this kind made between two lengths of No. 6 S.W.G. copper wire bound with No. 16 tinned copper wire. The ends of the two conductors are carefully cleaned and laid side by side for a distance of about three inches. The binding wire is then wound tightly over them, commencing

preferably at the middle of the joint, and working towards each end in turn, a few convolutions being wound over the single wire at each end of the joint. The joint is finished by carefully and completely soldering it into one mass, care being taken to avoid overheating it. A joint made in this way approaches as nearly as possible to perfection, for its resistance is less than that of the other portions of the conductor, and its mechanical strength is greater.

FIG. 329.

The method of jointing a covered stranded conductor is simple. Supposing it to be a 7-wire strand, the insulating covering is removed from each end for a distance of a few inches, care being taken to avoid nicking the copper. All the separate wires are then opened out and the centre wire on each of the ends to be joined is cut off short. The two sets of wires are next brought end to end, and laced together, just as would happen when the two hands are placed palm to palm, and the fingers of one hand placed between those of the other. This being done, the protruding ends of each conductor are wrapped closely round the other, the two wrappings being in opposite directions. The joint is then trimmed round with the pliers, and the whole well soldered together. The soldering is a more important matter than would at first sight appear, since the solder is relied upon to maintain the electrical continuity. Every care should therefore be taken that the copper surfaces are thoroughly cleaned before making the joint, that they are not handled more than is absolutely necessary, and steps should be taken, as far as possible, to prevent oxidation. A very good plan is to use tinned wire, and to employ only resin as a flux. The conductor-joint having been completed, the insulating covering is then made good. When the insulating material is india-rubber, pure rubber strips are tightly wound over the conductor in several layers, followed by a layer of prepared rubber

tape. To make the joint thoroughly reliable the covering should be vulcanised, which may be effected by immersion for about twenty minutes in a bath of sulphur gradually raised from just above its melting-point to a temperature of 154° C., and then for ten minutes in a bath of ozokerit, which is raised from 154° C. to 164° C.

When the conductors are to be laid underground, the chief difficulty to be contended with is the provision of efficient and durable insulation. The simplest method is to support the bare conductor by suitable insulators, after the manner described in Chapter XII. The maximum permissible distance between the insulators depends either upon the rigidity of the conductor or upon the tension which it can withstand. Since every insulator is a point of leakage, it is obviously necessary that their number should be reduced as far as possible.

In some electric lighting installations the bare conductors are supported by ordinary porcelain insulators fixed in a brick-work conduit with a concrete lining. In others, such as that in the Pall Mall district (London), in which the three-wire system is employed, the mains are carried in underground channels almost oblong in section, and made of cast-iron. At the junction of adjacent lengths a groove is formed in the sides of the channel, in which, at right angles to the length of the channel, is fitted a stout porcelain slab. The under edge of the slab is arched to allow the free flow of water along the bottom of the channel. The slab has also three deep vertical slots across the top, the centre one being somewhat narrower than the other two. Each conductor consists of a number of bare copper strips placed edgeways in the slots, and drawn tight enough to prevent contact laterally, while the depth of the strip is sufficient to prevent sagging. The centre conductor is formed of fewer strips than the outer mains; while the conductivity of all of them can readily be reduced beyond the points where branch circuits tap the mains, by reducing the number of strips. Long experience with underground chambers and channels, such as are employed for many other purposes, has shown that it is impossible to prevent the accumulation of water within them; hence the necessity for amply providing for the ready escape of water, that is to say, the conduit must be well drained. Electric light engineers have not yet had a suffi-

ciently lengthy experience to enable them to appreciate fully the real difficulties which await them, such as those due to the corrosion of the iron and the falling of scale from the roof and sides of the channel; and to the incrustations and fungoid growths which manifest themselves in damp underground chambers. It would appear to be essential that good drainage should be supplemented by ample ventilation. Even were a conduit to be made water-tight, there would still be sufficient moisture caused by condensation to oxidise the iron, and to make the surfaces of the insulators damp.

It will, however, be evident that were the pipe containing the conductors filled with some good liquid insulating material, this accumulation of moisture with the attending disadvantages would be avoided. Paraffin oil is a liquid which has remarkably high insulating properties, and is, therefore, available for this purpose, but with a conduit constructed in the ordinary way the quantity of oil required would be enormous. On account, however, of its high specific resistance, a thin film suffices to prevent leakage from one conductor to another, even though the potential difference between them be very great. The Brooks system is based upon this principle. The conductors are first covered with a coating of cotton, or other similar material, and then drawn into iron pipes, which are subsequently filled with and kept full of oil. Paraffin oil was originally employed, but great difficulty was experienced with it on account of its remarkable power of forcing its way through even such substances as cast-iron. Better results have been obtained with a much heavier and more viscid oil, such as resin oil, and the good insulation and other advantages which can thus be obtained render the system deserving of more attention than it has yet received.

Another method of insulating underground conductors, and the one generally adopted, is to cover the copper with some durable substance of high specific resistance, such as india-rubber.

In all such cases it is essential not only to efficiently insulate the conductor, but also to protect the insulating covering from deterioration by exposure, and to protect the whole cable from mechanical injury. When these points are very carefully

attended to, an installation with insulated underground cables for the mains is very reliable, and gives little or no trouble in maintenance. But carelessness in manufacture or laying, or the use of inferior materials, gives rise to troublesome and often very expensive repairs.

There is still a tendency towards false economy in this matter. A thin covering of the insulating material is placed over the conductor, and when new and absolutely perfect the insulation may test higher than is actually essential in practice. But the slightest indentation or abrasion of the covering, such as may easily happen and does happen, in handling during the process of laying, even if it does not quite expose the copper, leaves such a weak spot that the development of a 'fault' there becomes only a question of time. The insulating covering, of whatever material, should be of reasonable thickness, not so much for the purpose of obtaining an extremely high initial insulation-resistance, as to ensure its maintenance at a fairly good value. Gutta-percha must be used with caution. If not exposed to light and air, it is practically imperishable, and it may therefore be used with advantage under conditions which are at all similar to those obtaining in the case of a submarine telegraph cable; but it quickly cracks and perishes if employed in a dry, airy situation. In such cases india-rubber would be preferable, and when vulcanized rubber is employed, the copper requires to be tinned in order to protect it against the sulphur which such rubber contains. Gutta-percha softens at a lower temperature than does india-rubber, and hence is more likely to allow the conductor to become decentralised when heated by the current.

Generally speaking, india-rubber is the best material available for insulating purposes; but really good rubber is expensive, and the same may be said of the material which is usually sold as such; hence a large number of substitutes have been introduced. Some of them are fibrous in their constitution, and are impregnated with an insulating oil. Their specific resistances are lower than those of percha or rubber, but this is not a serious drawback provided the coating is sufficiently thick. They are not as a rule impervious to moisture, and require therefore a waterproof covering.

Bitumen is a good insulating material, but it softens at a low temperature, and even at normal temperatures it is so plastic that the weight of the conductor itself would cause it to sink through the coating. The processes employed by the Callender Bitumen Co. overcome these objections. The material is vulcanised or treated with sulphur, with the result that, while retaining its high insulating properties, it becomes rigid and holds the wire permanently in position, even though the temperature of the conductor be considerably raised. The conductor is usually of stranded copper wire, tinned to protect it from the sulphur. It is first coated with a sheath of the vulcanised bitumen, applied under heavy pressure in one solid layer to the required thickness. This sheathing is then covered with cotton tape treated with bitumen, the number of layers ranging from one to five ; the cable is passed through a bath of hot compound after each serving of tape. The next process, for underground cables, is to apply a coating of jute yarn, and after another passage through the bath to cover it with hemp braid. Most of the cables are subjected to this treatment, the higher degrees of insulation being obtained by increasing the thickness of the dielectric—that is, of the vulcanised bitumen. For the smaller cables, such as are employed for indoor work, a layer of parchment tape is interposed between the conductor and the bitumen.

For important underground work the Company has three distinct systems, the cables in all such cases being made as already described with the higher degree of insulation. In the first of these systems, a rectangular cast-iron trough is laid in a trench. The troughing is made in six-foot lengths, the thickness of the metal ranging from three- to five-sixteenths of an inch ; the internal dimensions vary according to the number and size of the cables, but in all cases the cable is kept at some considerable distance from the iron. One end of each length of the troughing fits into a socket made at the adjacent end of its neighbour. The two lengths are then bolted together and the joint sealed with bitumen. The cables are supported by a number of wooden bridges, generally placed at intervals of two feet. Each bridge before being placed in position is treated with bitumen, and has two or more vertical slots, according to the number of cables, each

slot being rounded at the bottom, and just wide enough to [illegible] cable. A small quantity of natural or unvulcanised bitum[illegible] run along the trough, and the bridges are imbedded in it befo[illegible] solidifies. The cables are then laid in position in their resp[illegible] slots, the dimensions of the wood being sufficient to keep them clear of each other and of the iron. The trough is next filled u[illegible] pure bitumen and covered in with a one-inch layer of concre[illegible] an iron lid. It may be urged as an objection to this system the cables having been once laid, cannot in the event of a occurring be withdrawn; but, on the other hand, the system p[illegible] of such good work being put in that the chances of a break can be made very remote.

The second of these systems is designed to allow the [illegible] which are similar to those used in the previous case, to be drawn separately. The channelling consists of blocks of bitu[illegible] concrete made in six-foot lengths and jointed by a saddle-p[illegible] the same material. The blocks are provided with longi[illegible] circular holes or 'ways,' varying in size and number ac[illegible] to the requirements, but only one cable is placed in each w[illegible] most cases there are either two, three, or four ways, the di[illegible] most frequently employed being $1\frac{1}{2}$, 2, or $2\frac{1}{2}$ inches.

Draw-boxes are provided at convenient intervals, and th[illegible] having been fixed together in the trench, the cables are d[illegible] This system has also the advantage that, should the cable [illegible] fail or give way, serious damage may be prevented from that the supporting material, *i.e.* the bituminous concret[illegible] insulator.

The saddle-pieces with which the joints are made emb[illegible] sides and bottom of the blocks, and are provided with two (one on either side of the joint), which are filled with bitu[illegible]

In the third system the insulating material is fibro[illegible] constitution and is sheathed in lead. Over the conductor a layer of parchment tape. Next to this is applied a rat[illegible] layer of fine yarn, which has been dried at a very high tem[illegible] and then impregnated with boiling bitumen under pressu[illegible] characteristic feature of this cable consists, in fact, in [illegible] cesses adopted for the complete exclusion of moisture Immediately after the impregnation is completed and [illegible]

bitumen is still hot, the lead sheathing is put on direct with the aid of hydraulic pressure. The subsequent treatment varies with circumstances, but it is usually necessary to protect the lead from mechanical injury and the chemical efforts of certain soils. For these purposes, the lead is passed through an asphalte bath and is then served with steel wire or ribbon, which is also covered with bitumenised tape or braid.

We have already described the method of making the splayed or long joint for stranded conductors, but in all Callender cables another form, known as the 'marriage' joint, is employed; a portion of the joint is illustrated in fig. 330. More skill and time are required to make this joint than are involved in the ordinary joint, but it has the advantage that the conductor is of uniform diameter throughout. Each strand is wound separately round the others, and is cut to such a length that it abuts against the end of a strand from the other side of the joint. The end-

Fig. 330.

to-end abutments occur at regular intervals, as can be gathered from the illustration; and the whole is well soldered. The covering is made good by pieces of materials identical with those already on the cables. In the case of the lead sheathing, an ordinary wiped joint might be employed, but owing to the uncertainty of always obtaining reliable plumbing work this method is not adopted. The cable ends are led through holes in the ends of a cast-iron joint-box, which after the ordinary insulating coating has been made good, is filled up with bitumen. A similar box, provided with three holes, is used at a T-joint.

A good type of electric lighting cable is manufactured by Messrs. Felten & Guilleaume, one form of which, designed for one of the mains on a three-wire circuit for incandescent lighting, is illustrated in fig. 331. The stranded core of high-conductivity copper is insulated with a layer of impregnated fibre, the thickness of which is about one-third the diameter of the conductor. Outside the fibre two coverings of lead are placed, as indicated by the

black concentric circles in the figure. Over this is a layer of jute treated with an impervious compound; and mechanical protection is afforded by a double sheathing of iron ribbon (shown white), the external covering being another serving of the impervious compound. This cable was constructed to be laid bare in a trench, and it contains the pilot wires which are necessary on an extensive parallel system. These two wires can be seen on the left of the conductor; they are of thin copper insulated with gutta-percha.

The lead sheathing is drawn on cold at an enormous pressure, and squeezes the fibre insulation into a solid mass. The two coatings of lead afford greater security against a small imperfection than could be obtained by a single coating with the same weight of metal.

FIG. 331

When the cables are laid in an iron troughing, the iron sheathing is dispensed with, and the pilot wires are laid separately.

Wires inside a building must be efficiently protected to avoid damage or accident, as well as to maintain the insulation. The usual plan is to run the wires along parallel grooves in a wood casing, as it is usually stipulated that the coverings of the two conductors should always be separated by an independent solid insulating substance. When it is necessary for one wire to cross another, a slip of wood is interposed. The casing can be made in a variety of forms, and if necessary can match the beading or cornice.

India-rubber covered with braided hemp or cotton forms about the best material for insulation for indoor work.

We have already described certain pieces of measuring apparatus, but there are a few other internal fittings to which some attention must be paid. Perhaps the most important of these is the switch,

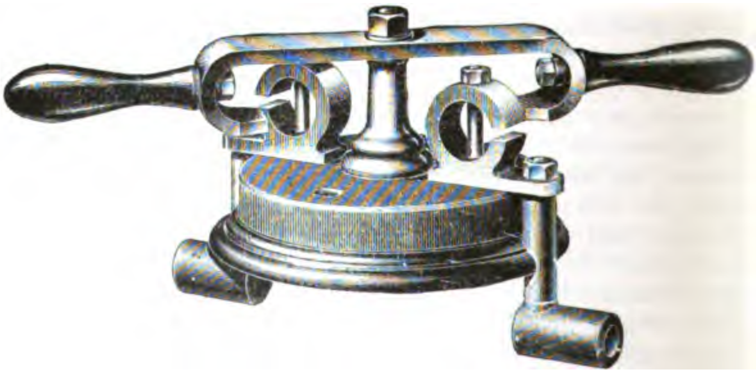
a piece of apparatus which is in constant use and for a variety of purposes, but chiefly to form a ready and expeditious means of making and breaking a circuit. In order that a switch may be capable of efficiently performing its functions, its metallic parts must be sufficiently massive to carry the required current without heating or offering any appreciable resistance ; the contact surfaces must for similar reasons be of ample area ; the moving contact piece must press firmly on to the fixed one ; and simple striking contacts must give place to rubbing contacts, to avoid partial insulation through accumulation of dust and metallic oxide films. The circuit should not be completed through the axle upon which the arm or lever travels, as dirt and dust are liable to accumulate at the bearing surfaces, and in time impair the efficiency of the switch. It is also preferable that the circuit should be broken at both ends of the switch-arm.

The switch should be so constructed that there is the minimum abrasion and wearing compatible with good and certain contact, and such parts as do wear away should be easily adjustable or cheaply renewable, so as to permit the re-establishment of good contact. In all cases, but more especially for currents of high E.M.F., the lever should be provided with a handle of insulating material; and the breaking distance through which the arm travels should be sufficient to prevent a spark following the retreating arm and setting up an arc. When contact is broken the current (especially if it is of a high electro-motive force, or if the circuit contains any apparatus having considerable self-induction) sparks across a portion at least of the air space in the effort to continue its course, and thereby volatilises a portion of the metal surfaces. If such an arc has been once established its maintenance is not a matter of great difficulty; and it is evident that such an arc is quite competent to start a serious fire, besides in any case damaging the switch contacts. It is advisable to provide a snap-action, so that the lever is set decidedly either on or off the fixed contact, the spring being so arranged that the lever is jerked quite away when it is turned almost out of contact. The terminals should never be so placed that in turning the handle there is any chance of the instrument being short-circuited by the operator's hand. The base of the instrument should be of

some good insulating material, not liable to warping or appreciable expansion or contraction. Wood, therefore, should never be used. What is required is a material which is non-inflammable, a good insulator, does not readily condense moisture, nor facilitate the accumulation of dust and dirt. Slate is a good material if free from impurities such as mineral streaks or veins; glazed porcelain condenses moisture freely, and is brittle. The conductors, especially those of the stranded type, should not be clamped under a nut or washer, but soldered into a socket or thimble which can be bolted on to the switch block.

The 'Ring contact' switch (fig. 332), made by Messrs. Drake & Gorham, is undoubtedly a good type for carrying heavy currents.

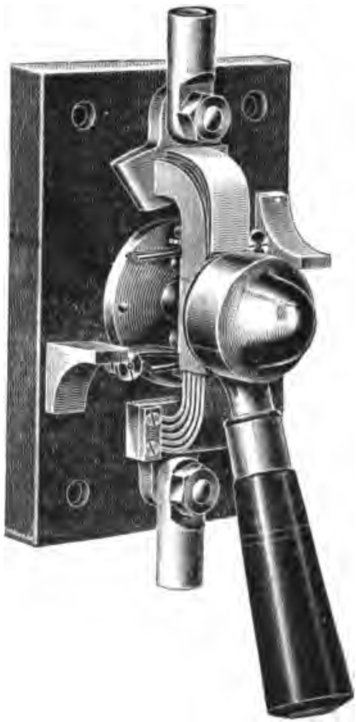
FIG. 332.



It is mounted on a slate base, each terminal clip consisting of a laminated split brass ring, the contact being made by forcing the connecting bar into the gap in the ring. This bar, which is a strip of stout brass, with, in the particular form illustrated, the ends bent round, is provided with substantial handles. As the contact surfaces wear away, the gap can be reduced by tightening up the bolt which it will be seen passes across the vertical diameter of the ring. The sockets to which the conductors are connected are bolted to lugs projecting from the bottom of each ring. This form of switch is made to carry currents up to 1,000 amperes.

The 'Diamond' switch (fig. 333), made by Messrs. Poole & White, is also a good type. The switch-bar consists of a number of—in this case five—bent strips of tough brass, which rub on to fixed brass blocks, and these blocks are bevelled to prevent the bar jarring against them, and at the same time to allow it to slide fully on to them, although the pressure is considerable. The switch has a quick break, almost instantaneous, owing to the action of a powerful bent spring, which is composed of a number of steel wires, as shown in the figure. This spring presses against a projection from the axle, which is edge-on when the switch is in the position shown, but which with a small movement is presented obliquely to the spring, allowing the latter to jerk the arm away clear of the contact blocks. These switches are likewise made to carry up to 1,000 amperes.

FIG. 333.

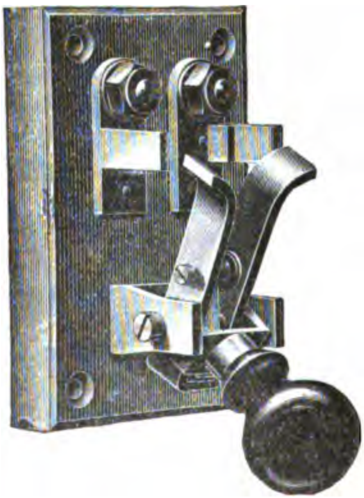


Another useful type of switch, which is rapidly increasing in favour is that illustrated in fig. 334, in which the lower part of the handle carries a heel piece which allows the pressure to be suddenly applied or withdrawn. In the latter case a spring fitted on the base presses against the contact arm and causes it to leave the contact blocks smartly. The well-known 'Tumler' switch used for small currents is constructed on very similar principles.

In another form of switch which is frequently used the movable arm consists wholly or in part of thin flexible copper strips, screwed

firmly into square tubes or sockets, and rubbing edgeways over solid brass or copper blocks. In one such switch the arm consists of a stiff flat spring terminating in square holders, in which the flexible brushes, composed of a great number of strips, are held by set screws. This type has the advantage that there is always an extensive contact surface, that adjustment is easy, that the brushes are comparatively inexpensive, and that they can be readily removed for cleaning or renewal. The switch made by the Acme Company, and illustrated in fig. 335, is somewhat similar in principle. In this case the brushes rub against the inner vertical faces of the contact blocks, instead of over the upper horizontal surface. But it will be noticed that the wear is taken up by moving the contact blocks inward by means of the set screws shown in the figure.

FIG. 334.



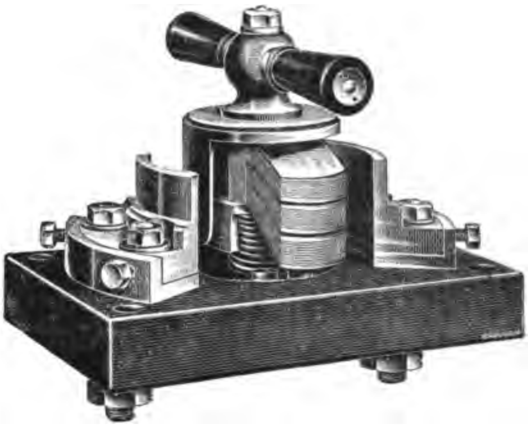
'Double-pole' switches are switches which disconnect both the positive and negative conductors simultaneously. They usually consist of a pair of 'single-pole' switches, such as those we have described, linked together by an insulating bar, both levers being actuated by a common handle.

A switch of some kind is required in connection with every incandescent lamp or group of lamps, and of this class there is a vast number in use, many of them being simple forms of those already described.

Fig. 336 illustrates a class of switch known as a wall socket, which is useful in cases where it is required to place a movable lamp in circuit at one or other of a number of positions, in such places as cellars, workshops, and libraries. The leads are joined to a pair of terminals in the larger block, which is permanently fixed in position. The movable block carries the flexible wires

leading to the lamp, the ends of the wires being connected to two split spring plugs, which can be pushed into the socket-piece and so complete the circuit through the lamp.

FIG. 335.



Switches have been made which snap 'on' as well as snap off, but they are mostly complicated in design, and, as the snapping on is of no material advantage, this objection is fatal.

Highly important as switches undoubtedly are in an electric light circuit, cut-outs cannot be said to be much less so. The function of a cut-out is primarily to prevent damage being done to the apparatus, the leads, or the building in which they are placed, by means of an unduly strong current; and the way in which it affords this protection is by automatically disconnecting the circuit when the current from some cause, accidental or otherwise, exceeds a certain predetermined limit.

FIG. 336.

There may be said to be two species of cut-outs—(*a*) those actuated by an electro-magnet, and (*b*) those carrying a piece of wire or foil which melts or fuses with a current of definite strength.

A magnetic cut-out consists essentially of a coil of wire placed in the main circuit and provided with a movable core, or armature,

to which is attached a strip of metal also forming a part of the main circuit. When the current rises above the prescribed strength, the coil attracts its core or armature with sufficient force to draw away the strip and break the main circuit. But it is necessary for the contact made by the strip with the ends of the main circuit to be very good and also frictionless, otherwise the pull required to break contact would be liable to vary. In the best instruments the two ends of the main circuit terminate in cups which are partly filled with mercury, after the manner illustrated in fig. 274. A horseshoe-shaped copper rod is attached at its centre to the armature, and each leg dips into one of the mercury cups. The contact is thus reliable, but there is a chance of serious sparking occurring at the mercury surface when the contact is broken with a heavy current, especially if any large electro-magnet having considerable self-induction is included in the circuit. The advantages of such a cut-out are, that it can readily be adjusted to act with certainty with any given current, either by varying the tension of an antagonistic spring, or by altering the centre of gravity of the moving piece. It can also be arranged to automatically restore the connection when the current falls again to a safe value. Although this latter arrangement is not as a rule adopted, the apparatus can be immediately restored to its normal state by hand, when the cause of the abnormal rise in the current has been discovered and removed. It is manifest that the resistance of the apparatus must be kept extremely low to avoid serious loss of power. It requires a certain amount of attention, and is expensive compared with the type next to be considered, viz. the simple fuse.

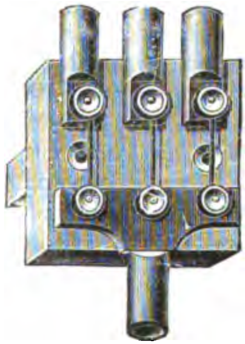
A fuse can be constructed so as to offer very little resistance, and therefore to absorb but little power. It must of course offer some resistance, since it is owing to the heat developed by the current in overcoming this resistance that the fuse is melted. Obviously a fuse made of a metal which has a low melting point requires comparatively little electrical energy to raise it to a state of fusion; and hence a fuse composed of such a metal may be made of lower resistance, and so absorb less power, than if a metal with a high melting point (such as platinum, 2,000° C.) were employed. In fact, with a well-designed fuse the chief cause of

loss of power is likely to be in the careless connection of its extremities to the terminals.

Such a cut-out has no working parts likely to get out of order or to need any attention, is very inexpensive, and, if properly designed, can be relied upon to act when the current reaches any particular strength, or at any rate within about 5 per cent. of it.

The fuse must be designed so as to break promptly and certainly, and manifestly it should not be of a material which might get red-hot before it melted, otherwise the danger from fire becomes serious. The lower the temperature at which the metal employed melts, the less is the danger thus incurred. It must not be forgotten that good conductors of electricity are also good conductors of heat, and that therefore the terminal screws to which the fuse is attached tend to conduct the heat away as well as to dissipate it by radiation. This fact necessitates the fuse being made rather longer than would otherwise be the case; and while the terminals must be sufficiently massive to allow good and reliable connection, they should not be unnecessarily so.

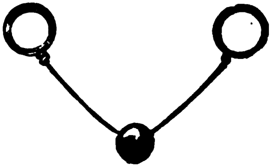
Fig. 337.



It is almost superfluous to add that the metal employed should be durable, and not subject to change from any cause such as oxidation. Platinum fulfils this condition admirably, and yet it is a most unsuitable material for general work on account of the high temperature at which it melts. It is, in fact, easy to maintain it at a bright red heat for a considerable length of time. Tin, however, melts at 235° C.; it is very durable, only slightly oxidisable, and, taking all things into consideration, is undoubtedly the best metal for a fuse. The base on which the fuse is mounted should be incombustible, and is usually of slate or glazed porcelain. It should also be protected with an incombustible cover, preferably of porcelain or brass. Where a number of fuses are mounted on a single base for purposes of distribution, as in fig. 337, they should be so arranged that the molten metal from a ruptured fuse should not be able to fall upon a neighbouring fuse.

Amongst the best work in this field is that performed by Mr. A. C. Cockburn, whose fuse is illustrated in fig. 338. The wire is of pure tin : a leaden shot is cast on at the middle of the wire, and its extremities terminate in small contact rings. These rings are slipped over the terminal screws, and, the nut being tightly screwed down, reliable contact is ensured. The distance between the screws is such that the sag of the wire is about equal to that shown in the figure, and immediately the current becomes strong enough to develop sufficient heat to soften the wire, the weight of the leaden shot causes a prompt and decided break. The disconnection thus occurs long before the temperature is reached at which the metal would become red hot, and before dry wood would ignite or even char. The rings at the ends of the wire enable the replacement of a fuse to be effected with ease and rapidity, and they have the further advantage that they avoid any uncertainty as to the length of wire actually in use.

FIG. 338.



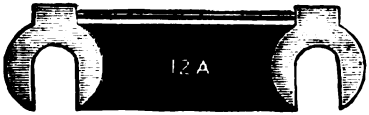
For heavy currents several comparatively small fuses are frequently joined in parallel, instead of employing a massive wire, an arrangement which makes more certain the breaking of the fuses when the particular current strength is exceeded.

FIG. 339.

An excellent type of cut-out is made by Messrs. Verity & Sons ; one of the double-pole form is illustrated in fig. 339. The conductors are secured to the terminals on the under side of the glazed porcelain, the fuses joining the upper terminals together and so completing the circuit. A porcelain cover is screwed over the cut-out to protect it from injury. The most interesting part is, however, the fuse, which is illustrated in fig. 340. The fuse wire is fixed between two brass mounts supported by a strip of hard fibre. The brass mounts are clamped in the terminals of the cut-

out, the slots allowing a renewal to be made very expeditiously. A slight modification of this type is illustrated in fig. 341, which represents a six-way single-pole distribution board; a single conductor is connected to the long brass bar on the lower portion of the slate base, and the current is then divided between the six smaller circuits (taking up to ten amperes each) which branch out therefrom. The best practice is to insert a fuse at these points, and the fuses

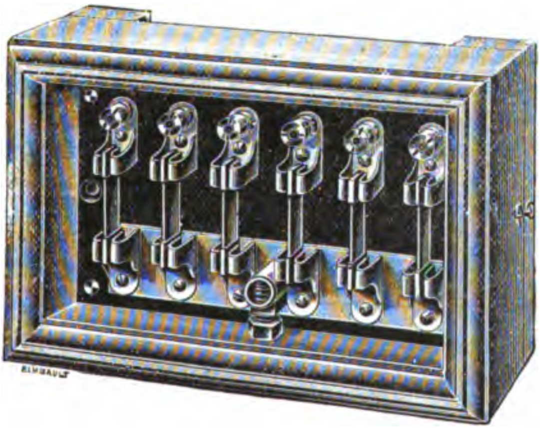
FIG. 340.



illustrated are provided with flat brass mounts, which are simply forced in between a pair of stiff bent brass springs at each end. Renewal is therefore very easy.

Several simple cut-outs are also made by the Edison and Swan Electric Light Company, and one of them is illustrated in fig. 342. This is a double-pole cut-out—that is to say, one which

FIG. 341.



introduces a fuse into both the conductors of a circuit. The cut-out is made on the same principle as the collar of the Edison lamp (p. 647), the fuse being mounted on a plug. One of these plugs, A, is shown in position in the figure. The upper socket

is shown without its plug, and the method of completing the circuit through the cut-out is there made evident. Many other types of fusible cut-outs are in use, but those described are typical of the best for general work.

FIG. 342.

An illustration of a method by which a cut-out may be applied to protect a suspended lamp is furnished by fig. 343, which shows the porcelain base of a ceiling-rose. The leads enter through holes in the base, and are connected each to a small brass block or strip; one of these blocks is also connected to one lamp terminal, and the other block to one end of the safety fuse shown at the back of the figure. The other end of the fuse and the other terminal of the lamp are joined to the third brass block. The flexible double wire by which the lamp is suspended is threaded through a hole in the centre of the cover, which screws on to the base, and which should be provided with a means for clamping the flexible conductors, and thereby taking the strain due to the weight of the lamp and its fittings, instead of throwing that strain on to the screws to which the ends of the flexible wires are secured.

FIG. 343.

One possible objection to the use of a fuse is that when it does act under the influence of a too powerful current it is destroyed, breaks the circuit of the lamp or lamps, and must be replaced

before the circuit is again available. It will be evident that such cut-outs must be cheap, and placed in accessible situations; but, after all, a cut-out is a somewhat clumsy device. It is not an engineering job, and its too extensive use bespeaks bad work or a want of confidence on the part of those who thus use it. The number employed should be made as small as possible, for every one is a source of leakage, and often a source of danger.

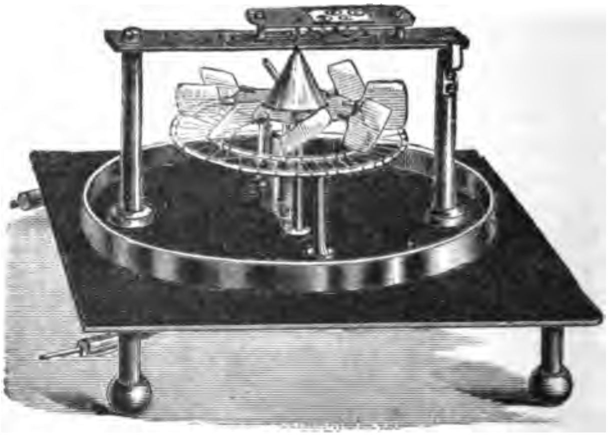
In a previous chapter we have described certain instruments called ammeters, which are capable of indicating the number of amperes of current flowing through them at any particular moment, but which are unable to measure the actual quantity of electricity passed through them during any given time. In just the same way a thermometer indicates the temperature at any moment, but gives no idea of the quantity of heat actually developed or absorbed. In the commercial distribution of electricity for lighting or other purposes, it is essential that a 'meter' should be provided which is capable of measuring and by some means recording the quantity of electricity supplied to any one consumer during, say, a month or three months. The unit quantity of electricity is the coulomb—that is, the amount transferred by a current of one ampere during one second; hence an instrument such as that referred to might aptly be called a coulomb-meter.

The coulomb is, however, too small to serve as a unit for electric lighting work, and it has been usual to employ as a unit the quantity of electricity transferred by a current, one ampere in strength, during one hour, this unit being known as the 'ampere-hour.' If, for example, a secondary cell were allowed to maintain a current of 15 amperes for $2\frac{1}{2}$ hours, the *quantity* of electricity obtained from the cell during that time would be $15 \times 2{\cdot}5 = 37{\cdot}5$ ampere-hours, and the amount of electrical energy developed could be found by multiplying by the pressure in volts. But even this larger unit is somewhat small for the measurement of supply on an extensive scale, and a still larger unit, known as the Board of Trade unit, has taken its place. It is equal to that amount of electrical energy which is developed or absorbed by a current of 1,000 amperes at a pressure of one volt during one hour. It is therefore equal to 1,000 ampere-volt-hours.

This Board of Trade unit is, then, the unit by which the elec-

tricity supplied is measured and charged. In most cases a certain piece of apparatus is introduced to indicate the number of ampere-hours supplied to the consumer's lamps, and this quantity multiplied by the pressure in volts and divided by 1,000 gives the number of Board of Trade units upon which the charge is based. But it is, unfortunately, far from easy to measure a quantity of electricity satisfactorily on a commercial scale. In fact, the instrument most urgently needed in the electrical world at the present moment is a simple, reliable, cheap, and compact quantity meter.

FIG. 344.



Many efforts have been made to produce such an instrument, and although some practical forms have been brought into use, much yet remains to be done by the usual process of development.

The simplest in principle, and perhaps also the most interesting, is that devised by Professor Forbes. It is based upon the heating effect of the current, and is consequently available for use with alternating currents.

The apparatus is illustrated in fig. 344. It consists of two concentric copper rings, supported at a little distance above the base and bridged across by a number of short fine wires. The current enters at one ring and leaves it by the other, passing

through the whole of the fine wires in parallel, the resistance offered by the wires being about $\frac{1}{100}$th of an ohm. The quantity of heat developed in these wires affords the means of estimating the quantity of electricity which passes. When the wires become warm the heat is imparted to the adjacent air, which expands and rises, so that a continual upward current of air is maintained during the whole time that the current is flowing, the strength of the air-current varying of course with the extent to which the wires are heated. A small pillar carrying a steel needle point rises through the centre of the rings, and a thin paper cone with a ruby bearing at its apex rests on the needle point. The base of the paper cone is attached to a small horizontal mica disc, from the edge of which project eight arms made of pith, each carrying a very thin mica vane, inclined at an angle of 45° to the horizontal, and placed directly over the fine cross wires.

The ascending air currents caused by the passage of electricity strike against the under side of the vanes, and cause them and the paper cone to rotate; the stronger the current of electricity the more powerful are the air currents and the greater the number of revolutions in a given time. It is, therefore, only necessary to add some device for recording the number of revolutions in order to estimate the quantity of electricity which has passed through the instrument.

The apex of the paper cone consists of a small aluminium cone, to which is attached the ruby bearing above referred to, and which also carries above the apex a small steel pinion, gearing into a train of wheels as shown in the figure. The train records the number of revolutions in the ordinary manner; but it will readily be apparent that, since the force which causes the rotation is so feeble, the slightest friction would be inadmissible, and the whole of the moving parts must be extremely light and delicate. In fact, beautiful as the principle is, it is to be feared that it will be difficult to develop it into a thoroughly practical instrument.

A quantity meter also based upon an interesting principle, and which in spite of many difficulties has been brought into a practical form, is that of Mr. Ferranti. We know that a conductor when placed in a certain position in a magnetic field is urged to a new

position in, or entirely out of, that field, immediately a current is passed through the conductor. If any portion of the conductor is movable independently of the remainder, we can move that portion only by sending all or nearly all of the current through it. A somewhat striking case is that of a liquid conductor, such as acidulated water or mercury, for the liquid can be kept continually in motion by placing the containing vessel in a powerful field, and sending a current through the liquid. If the lines of force of the field and those emanating from that portion of the liquid which is carrying the current do not happen to coincide, then that portion will be urged to a new position just as a copper wire would be, its place being taken by more of the liquid, which undergoes a similar treatment.

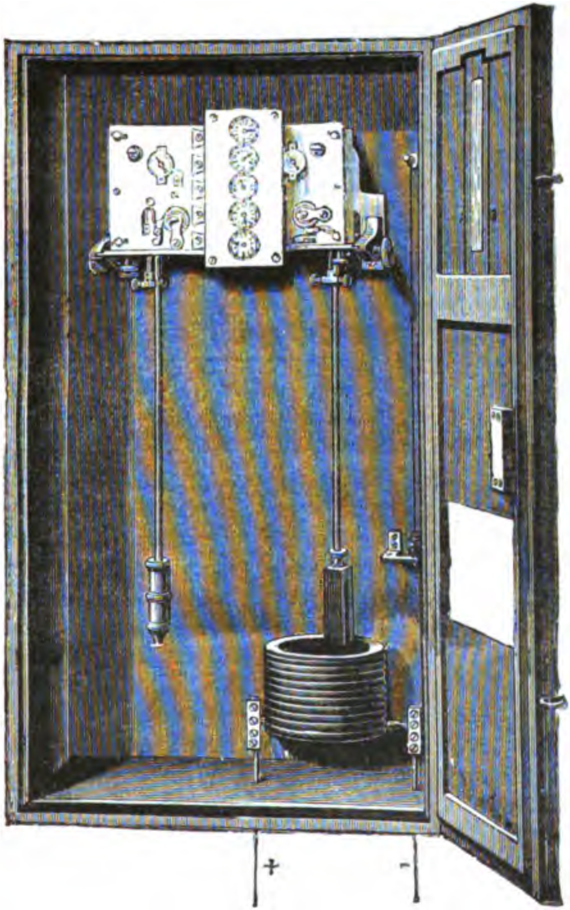
In Mr. Ferranti's meter, which is based upon this principle, the liquid employed is pure mercury. This is contained in a rather shallow circular vessel, above which is placed a solenoid fitted with a hollow iron core and a sheath, so disposed as to project a very powerful field vertically through the mercury. The current is led to the mercury at the centre of the vessel, leaves it at the circumference, and then passes through the magnetising solenoid.

Now the liquid conductor is urged to move in a direction at right angles to that in which the current is flowing through it, and also at right angles to the lines of force of the field. The direction of the current is radial, and supposing the lines of force to be projected vertically downward, the liquid will rotate in a right-handed direction as viewed from above. The force with which the mercury is urged to rotate, is proportional to the strength of the current flowing through it and to the strength of the fixed field. This field might be kept constant; or by employing the same current to excite the solenoid, and never allowing the iron to approach the saturation point, the field may be made to vary with the current, when the force tending to produce rotation will be proportional to the square of the current.

The mercury in rotating carries with it a light float, which is attached to the lower end of a light rod terminating at its upper extremity in a pinion which gears into a wheel forming part of the mechanism employed to indicate the number of revolutions made by the float. Of course the force acting is very small, and any

appreciable friction would seriously affect the indications ; but all these difficulties have been overcome, and reliable instruments based upon this principle are now in use.

FIG. 345



Another good meter which is extensively employed is the Aron Electricity Meter, illustrated in fig. 345. It is provided with the

usual speed-counting index, which is actuated by the difference in the speed of rotation of two distinct sets of clockwork. Each set is furnished with a pendulum, both pendulums being adjusted to oscillate at exactly the same rate in the absence of any disturbing element. The bob of the pendulum shown on the left in the figure is an ordinary weight, but that of the right-hand pendulum is a permanent magnet. So long as both pendulums continue to oscillate at exactly the same rate, no movement of the indicating pointers takes place, but they begin to indicate directly the right-hand pendulum is accelerated. This acceleration is made to take place by means of a solenoid fixed underneath the magnet, and through which the main current passes. As the acceleration is proportional to the strength of the current, it is evident that the instrument can be so adjusted that the index will indicate in ampere-hours. To make this or any similar meter serve the purpose of an energy meter, it is necessary to multiply the ampere-hours by the standard pressure at which the current is supplied, and hence the accuracy of the result depends quite as much upon the constancy of the pressure as it does upon the accuracy of the instrument.

An entirely different type of meter, which also measures in ampere-hours, is that based upon the electrolytic properties of the current, and which possesses the advantage that no delicate mechanism need be employed in connection with it. When a current is passed through a solution containing a metal, such as nitrate of silver or sulphate of copper, the solution is decomposed, and the metal which it contained is deposited on the wire or strip of metal by which the current *leaves* the liquid. Such a wire or strip by which the current leaves or enters the liquid is called an electrode. Suppose, for example, a solution of nitrate of silver with silver electrodes to be employed, then pure silver would be deposited from the solution upon that electrode by which the current leaves. Moreover, an exactly equal quantity of silver would be dissolved from the other electrode; this might easily be proved by weighing before and after the passage of a current, for it wouid be found that the one had lost in weight just as much as the other had gained. The solution, then, remains as rich in metal as it was before the passage of the current; but if the electrode by which the current

enters were made of carbon, or an unassailable metal like platinum, the solution would lose just as much metal as is deposited on the other electrode, the carbon or platinum not being dissolved at all.

It is a most important fact that the weight of metal deposited in this manner is exactly proportional to the quantity of electricity which has passed through the solution, irrespective, within wide limits, of the density of the solution or the strength of the current at any part of the time. It follows that, after having ascertained the weight of any metal which is deposited by a coulomb of electricity, or by an ampere-hour of electricity, we can always calculate exactly the quantity of electricity which has been transferred on any occasion, provided we find out what weight of that metal the current has deposited. Now, the solutions which at present concern us most are nitrate of silver, sulphate of zinc, and sulphate of copper, and it has been found by experiment that one coulomb (or ampere-second) is capable of depositing from these solutions 1·118 milligramme of silver, 0·33696 milligramme of zinc, and 0·32709 milligramme of copper respectively. The ampere-hour, being 3,600 times greater than the coulomb, deposits 4024·8 milligrammes of silver, 1213·056 milligrammes of zinc, or 1177·524 milligrammes of copper. So long as the total quantity of current which passes is the same, it is immaterial whether the deposition is effected by a weak current flowing for a long time or a stronger current flowing for a correspondingly shorter time. Thus a current of half an ampere flowing for 48 hours will deposit the same weight of copper as a current of 16 amperes flowing for $1\frac{1}{2}$ hour; in either case the total quantity of electricity is 24 ampere-hours. It is necessary, however, to take care that the surface of the electrode shall be ample, otherwise the metal is deposited so rapidly on a small surface that it becomes granular, and does not adhere.

Now suppose we take a vessel containing a solution of zinc-sulphate, and dip into the solution two zinc strips which have been accurately weighed. If, by suitable connections, we insert this arrangement in one of the main leads of an electric light circuit, zinc will be dissolved from one electrode, and an equal amount deposited on the other whenever a current is passing. If at the end of a month the plates are removed, carefully dried, and weighed

again, the total amount of electricity which has during that period been supplied to the lamp circuit can be very accurately estimated. Slight impurities and local actions may in practice prevent the gain of the one being exactly equal to the loss of the other, but by weighing them both and taking the mean of the loss and gain, a more reliable result can be arrived at. As a rule, however, only the loss on the plate by which the current enters the cell is taken as a measure of the quantity of current which has passed. Suppose this loss amounted to 1,213 grammes, then the quantity of electricity upon which the charge would be based would be 1,000 ampere-hours.

The 'chemical' meter of Edison is constructed upon this principle, and it will be as well to point out a few of the possible sources of trouble and inaccuracy in the simple arrangement just mentioned before describing the practical form of the meter.

The cell offers some resistance to the passage of the current, depending upon the size of the plates and their distance apart, and in order to allow it to be placed directly in an ordinary electric light main, the size of the plates would have to be unduly large. It is necessary, therefore, to use the cell as a shunt, bridging over a short portion of the main circuit having a resistance equal to, say, $\frac{1}{999}$ of its own; in that case the meter measures $\frac{1}{1000}$ of the total current flowing.

But then temperature variations alter the resistances sufficiently to cause grave errors in the results. A rise in temperature, for instance, reduces the resistance of the liquid, but increases that of the portion of the main conductor which is shunted by the cell. Both these effects tend to cause an increase in the proportion of the current flowing through the meter, and such variations must in some way be compensated for.

Moreover, the temperature may fall low enough to freeze the liquid. Also, since any external cause which cools the liquid or the shunted metallic conductor, or both, makes the meter register lower than it should do, care must be taken to so place these parts as to avoid leading the consumer into temptation. For similar reasons the terminals of a meter should never be exposed, nor any other facilities given for short-circuiting the apparatus.

The practical form of the Edison meter, as fitted for use in a

simple circuit, and in which these difficulties are overcome, is illustrated in fig. 346. At the bottom of the case is an incandescent lamp, which is automatically thrown into circuit whenever the temperature approaches the freezing point, and so keeps the solution from freezing. Above the lamp is placed a stout zigzag strip of German silver, which is joined up in the main circuit. It offers but little resistance, and, since its temperature coefficient is small, this resistance varies but slightly through ordinary changes. Above this strip two cells are placed, each containing two zinc plates immersed in a sulphate of zinc solution. The zinc is deposited at a definitely faster rate in one cell than in the other, and an additional check obtained by comparison of the two cells. The difference in the rate of deposition is effected by causing one cell to bridge a larger portion of the German silver strip than the other; the dividing terminal is seen in the figure at the end of the second bend from the right. The most important of the possible sources of error is that due to the temperature variation of the resistance of the liquid. This is compensated for and the resistance of the cell circuit kept constant in a very simple manner. When the temperature rises the resistance of the liquid *decreases*, but the resistance of a metal (copper for instance) *increases*. A spiral of copper wire is joined in series with each cell, of such a resistance that with a given rise in temperature the resistance of the spiral increases by just as much as the resistance of the liquid is de-

FIG. 346.

creased. These spirals are placed behind the cells and are not visible in the figure.

The meter is placed in the circuit of one of the mains feeding the group of lamps in which the electricity consumed is required to be measured.

The variation of the resistance of the German silver strip caused by temperature changes is not sufficient to introduce any great error. As a rule its resistance is $\frac{1}{999}$ that of the cells and compensating wire, so that the cell measures $\frac{1}{1000}$ of the total current passing through the main circuit.

The method of throwing the heating lamp in circuit when the temperature falls too low is simple and ingenious. One terminal of the lamp is connected to one of the mains, and its other to a small contact stud placed just above the holder. Above this stud is another contact, carried at the end of a long straight compound metal strip, which is fixed at the other end (to the left in the figure) and connected to the other main. The strip is formed of two metals, which expand or contract unequally when the temperature is varied. Under ordinary circumstances the two contact studs are kept apart; but when the temperature falls the compound strip bends or curls downward, and the adjustment is such that contact is made and the lamp thrown in circuit when the temperature approaches within two or three degrees of freezing-point

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[Every dash (   ) stands for a word in the line preceding it.]

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